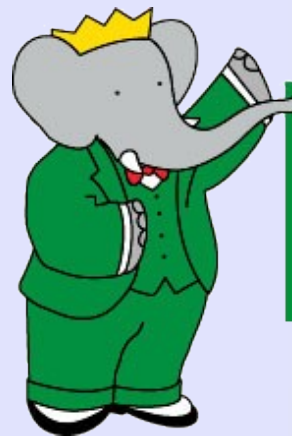


# Searching for Dark Matter with BaBar: Invisible Decays of the $Y(1S)$ Meson

Lucas Winstrom  
University of California, Santa Cruz



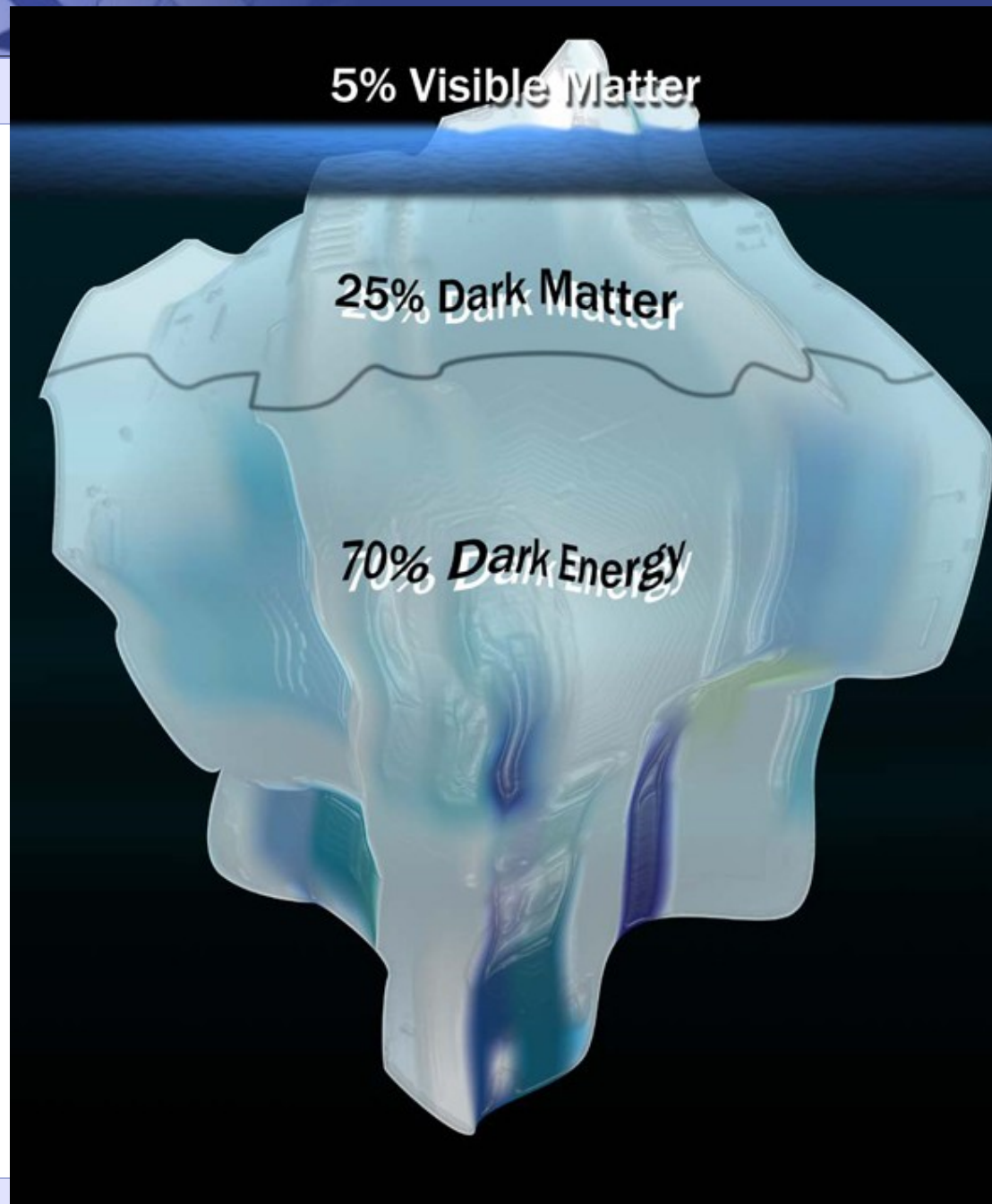
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# Outline

- ▶ Theoretical motivation for this search
- ▶ The BaBar detector and dataset
- ▶ Analyzing the dataset and measuring the invisible branching fraction of the  $Y(1S)$  meson
- ▶ Systematic errors – still in progress!
- ▶ Conclusion

# Dark Matter

- ▶ 25% of energy in the universe
- ▶ WIMP's typically ~10's of GeV to several TeV
- ▶ MSSM neutralino must be  $>6$  GeV
- ▶ What about lighter dark matter?



# Dark Matter Accessible to Colliders

## ► Lighter Dark Matter<sup>1</sup>

### • Astrophysical Evidence

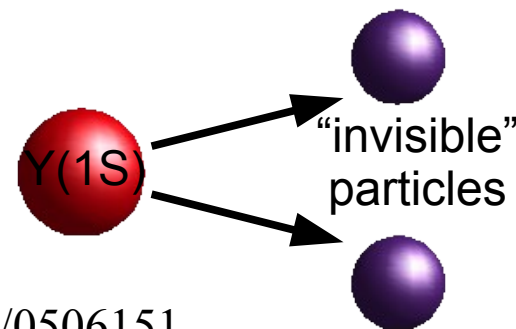
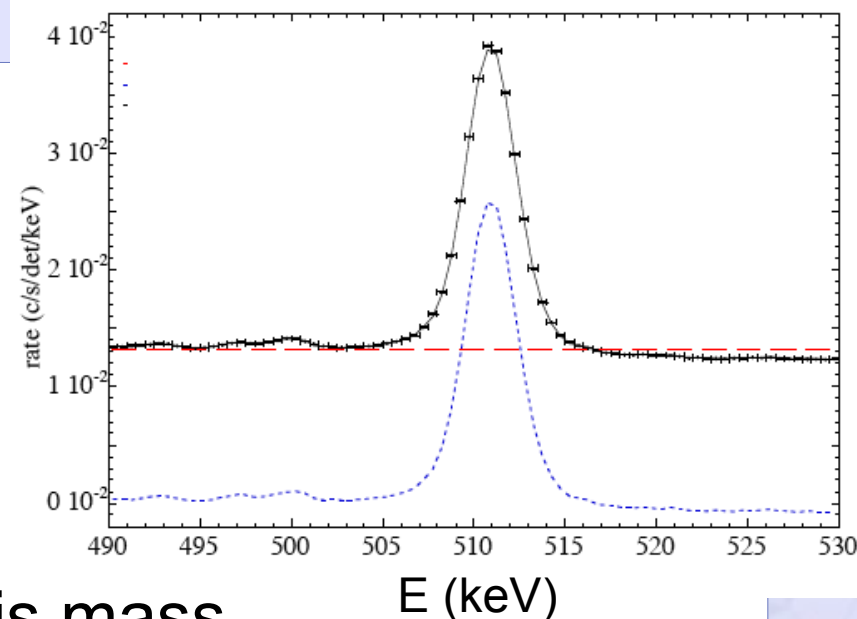
- 511 keV photons from galactic center<sup>2</sup>
- Implies  $DM < \sim 100 \text{ MeV}$ <sup>3</sup>

### • NMSSM<sup>4</sup> can give DM with this mass

### • Low mass dark matter can couple to $Y(1S)$

### • Allows $Y(1S)$ to decay invisibly

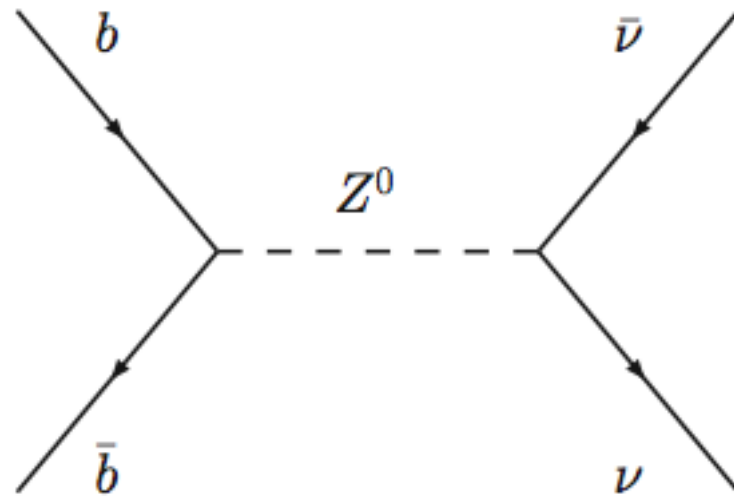
- s-wave –  $BF = 4.2 \cdot 10^{-4}$
- p-wave –  $BF = 1.8 \cdot 10^{-3}$



1. McElrath, Bob, Phys. Rev. D72 103508 (2005) arXiv:hep-ph/0506151
2. P. Jean, et.al. Astron.Astrophys. 407 (2003) L55 arXiv:astro-ph/0309484v1
3. C. Boehm, et. al. Phys.Rev.Lett. 92 (2004) 101301 arXiv:astro-ph/0309686v3
4. McElrath, Bob, arXiv:0712.0016v2

# Standard Model Invisible $Y(1S)$ Decay

- ▶ The Standard Model Prediction<sup>1</sup> for the branching fraction of  $Y(1S)$  invisible decay is  $\sim 1 \cdot 10^{-5}$



- ▶ We will be able to set an upper limit at a 90% confidence  $\sim 10^{-4}$ , so this is a search for new physics enhancing this decay

1. Chang, L. N. and Lebedev, O. and Ng, J. N., Phys. Lett. B441 419-424 (1998) hep-ph/9806487



# New Physics Potential

- ▶ Unparticles<sup>1,2</sup>
  - Unparticles have a continuous mass spectrum
  - Measurement constrains the dimensionality of a scale invariant sector and the energy scale of this new physics
- ▶  $Y(1S) \rightarrow$  “invisible” measurement cannot differentiate between these scenarios
- ▶ Current limits on this decay come from Belle at  $BF < 2.5 \cdot 10^{-3} [90\%CL]^3$

1. Georgi, Howard Phys.Rev.Lett.98:221601,2007      arXiv:hep-ph/0703260v3

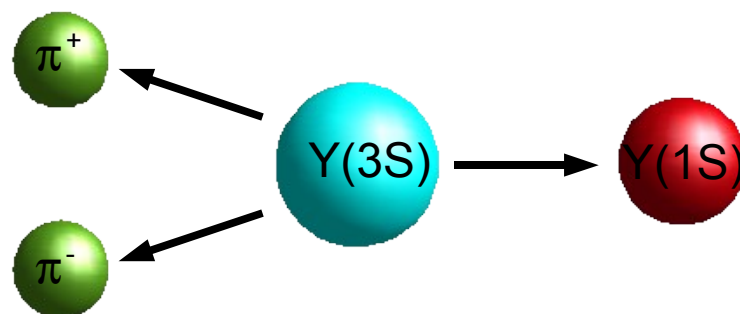
2. Shao-Long Chen, Xiao-Gang He, Ho-Chin Tsai JHEP 0711:010,2007      arXiv:0707.0187v3

3. Tajima, O. and others, Phys. Rev. Lett. 98 132001 (2007) hep-ex/0611041

# Invisible Decay of the Y(1S)

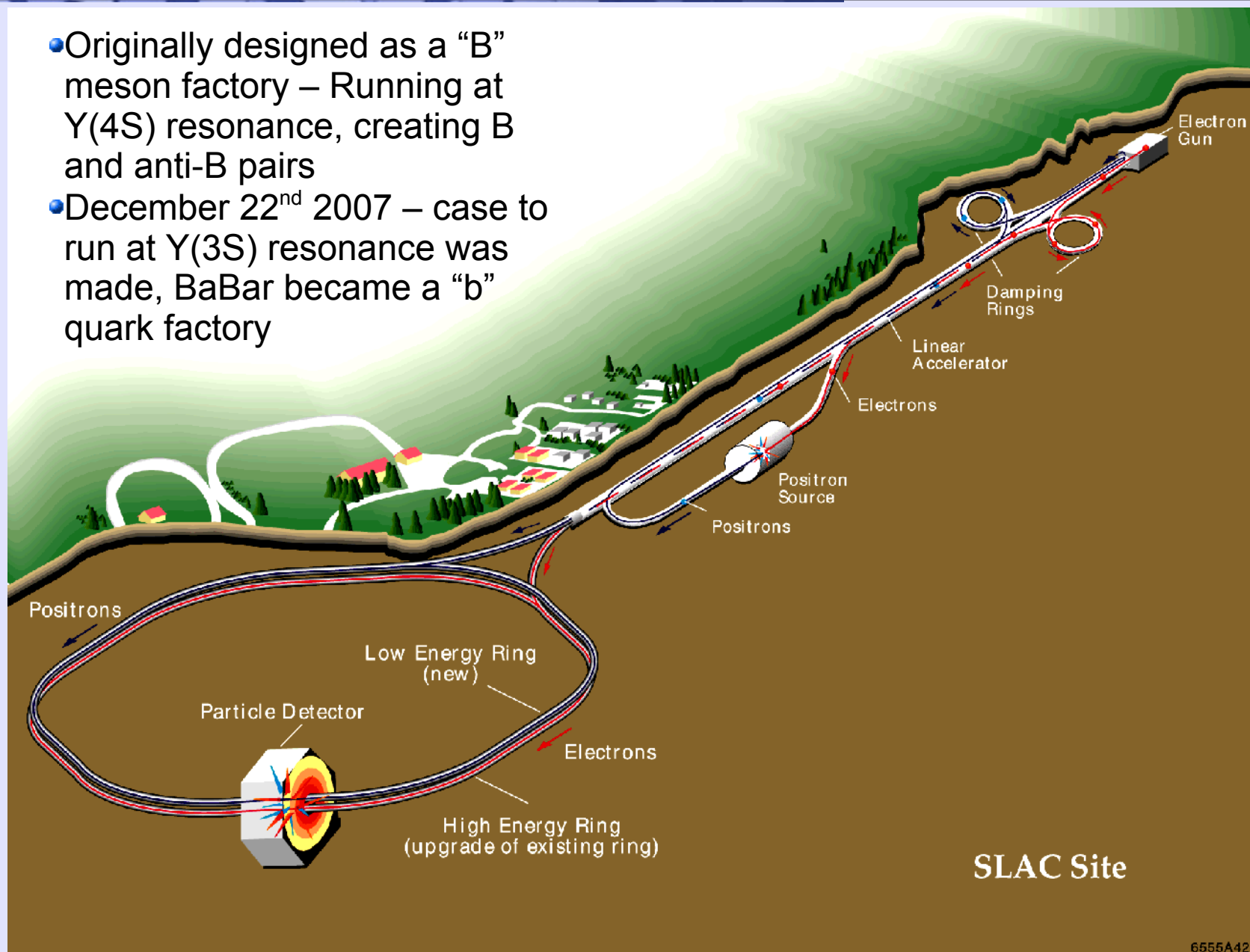
## ► How does one detect an “invisible” decay?

- BaBar has gathered a collection of Y(3S) mesons
- The Y(3S) has a decay mode of  $Y(3S) \rightarrow Y(1S)\pi^+\pi^-$ , providing a data set of Y(1S) particles that can be identified without a visible decay by the presence of these two pions



# Y(3S) Physics at BaBar

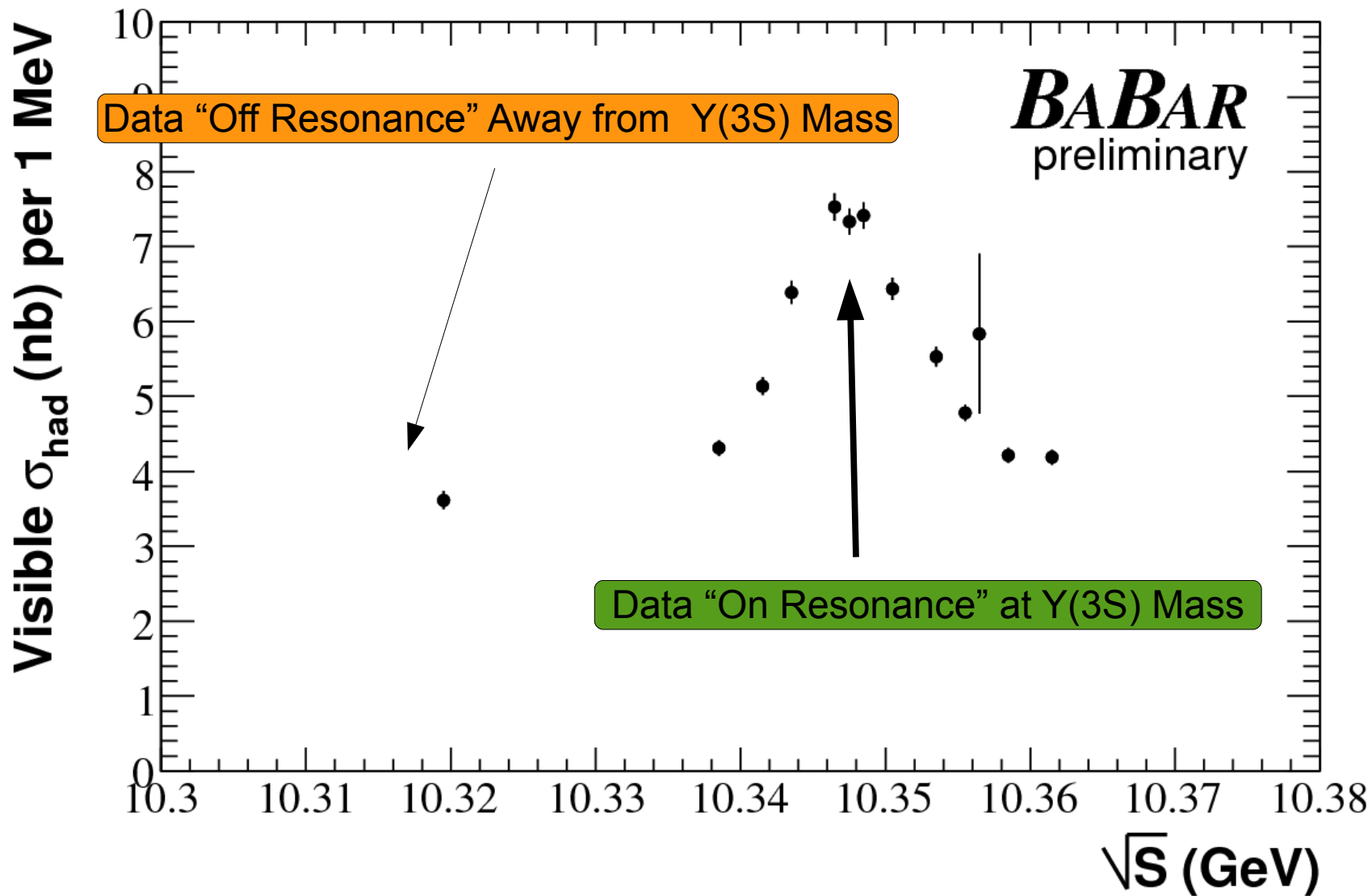
- Originally designed as a “B” meson factory – Running at Y(4S) resonance, creating B and anti-B pairs
- December 22<sup>nd</sup> 2007 – case to run at Y(3S) resonance was made, BaBar became a “b” quark factory



6555A42

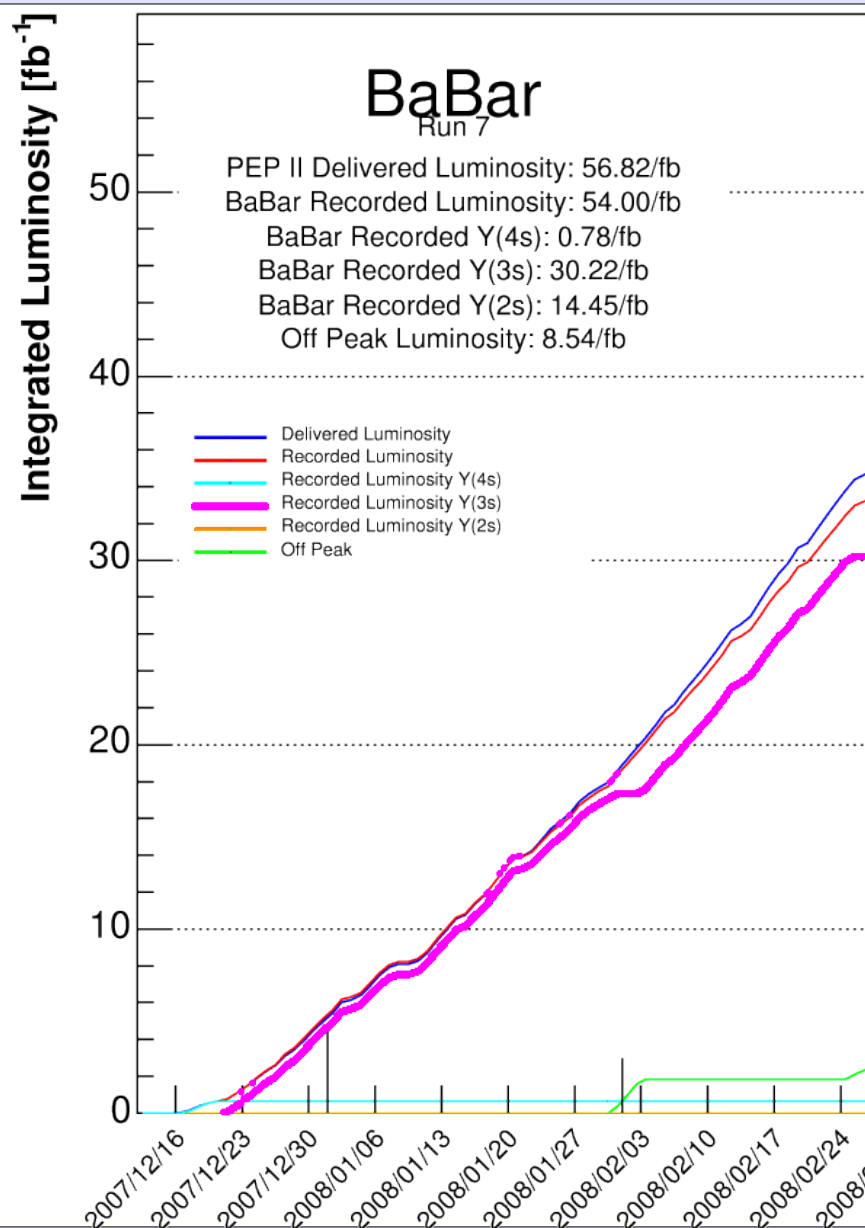


# Y(3S) Physics at BaBar



# Y(3S) Physics at BaBar

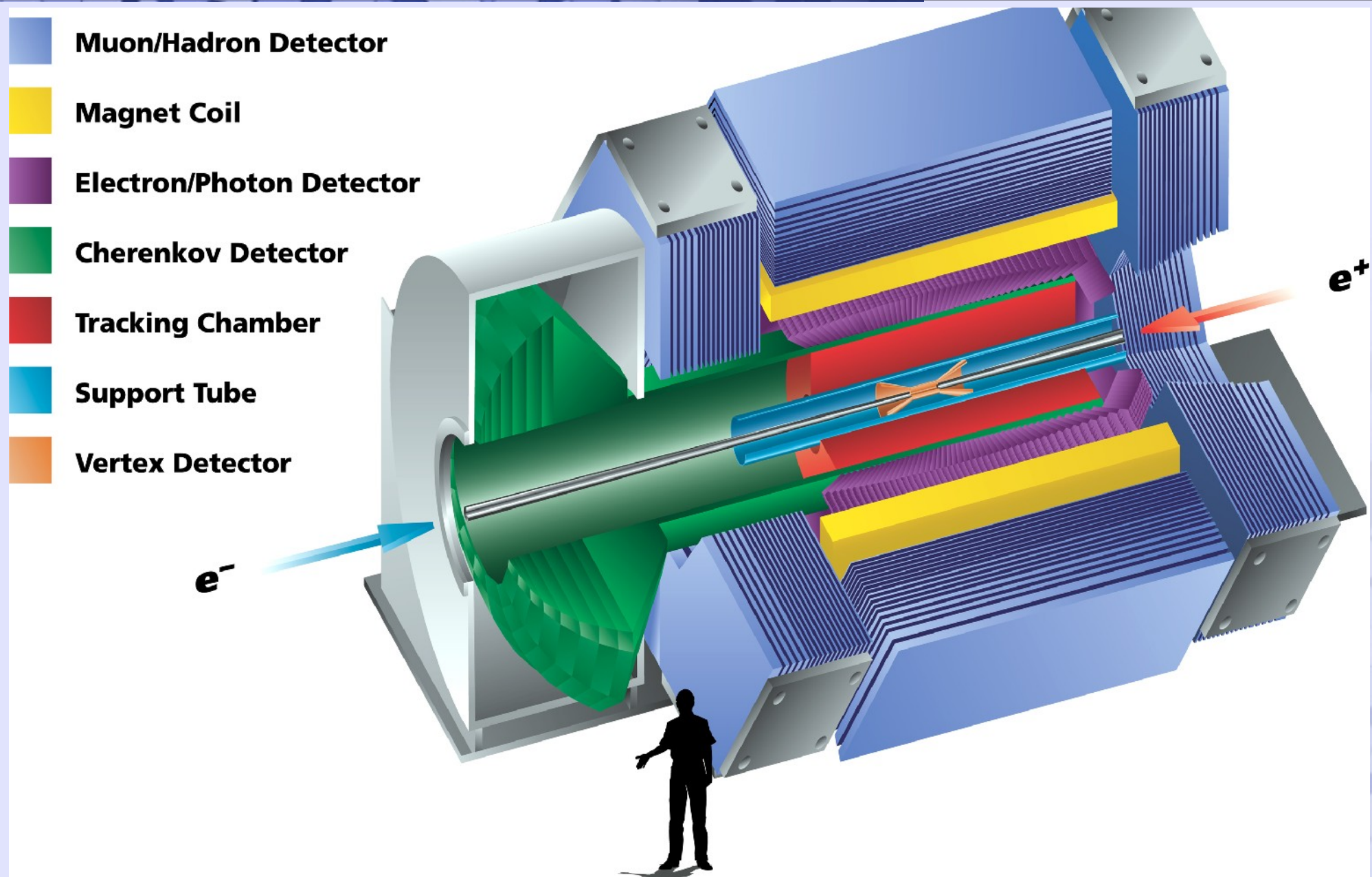
As of 2008/04/11 00:00



122 Million Y(3S) at BaBar  
11 Million at Belle  
6 Million at CLEO

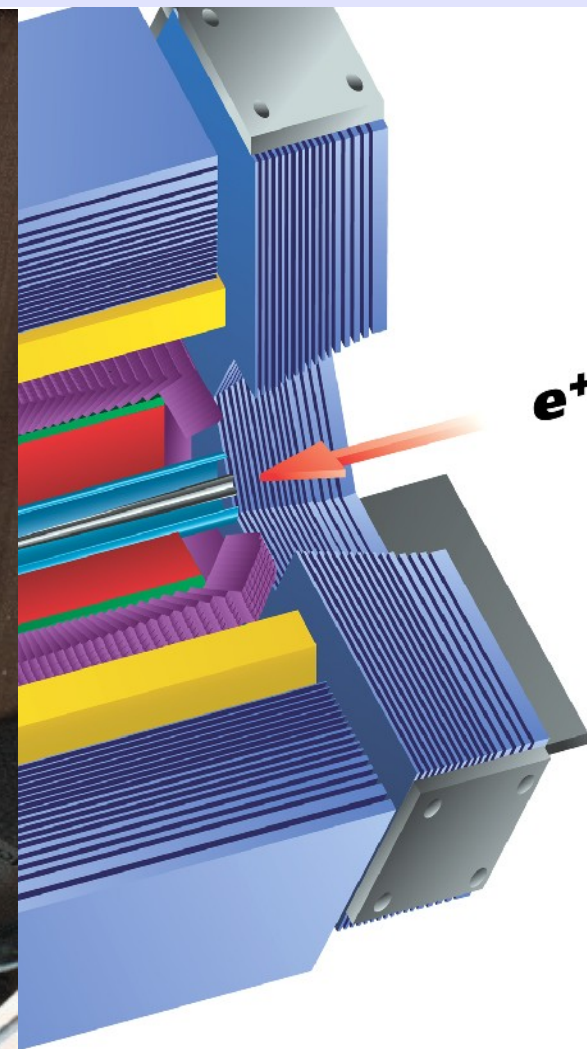
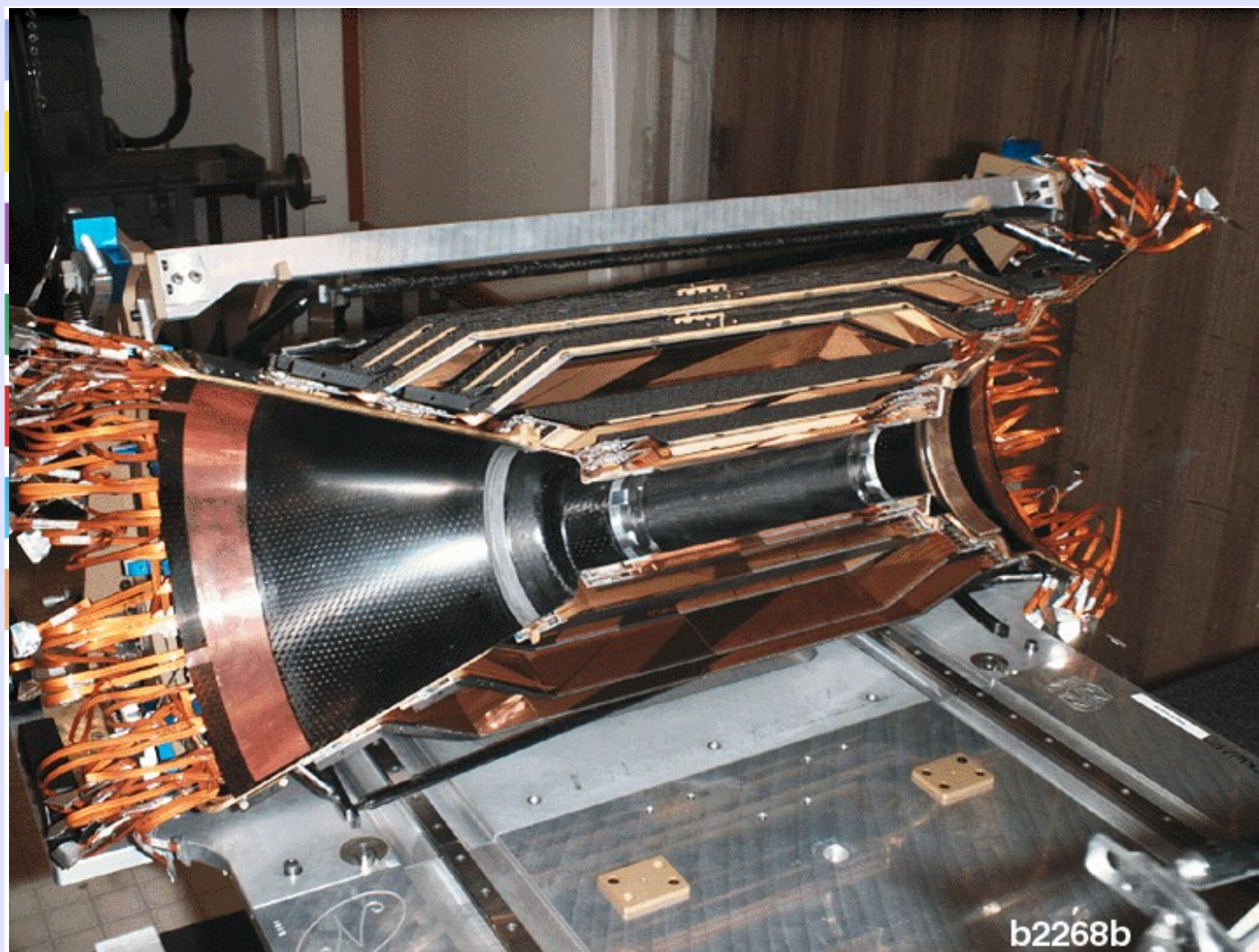
122 Million Y(3S) with a  
branching fraction of  
0.0448 to  $Y(1S)\pi^+\pi^-$   
gives 5.5 Million  
potential Y(1S) mesons  
that can be identified

# The BaBar Detector





# The Silicon Vertex Detector

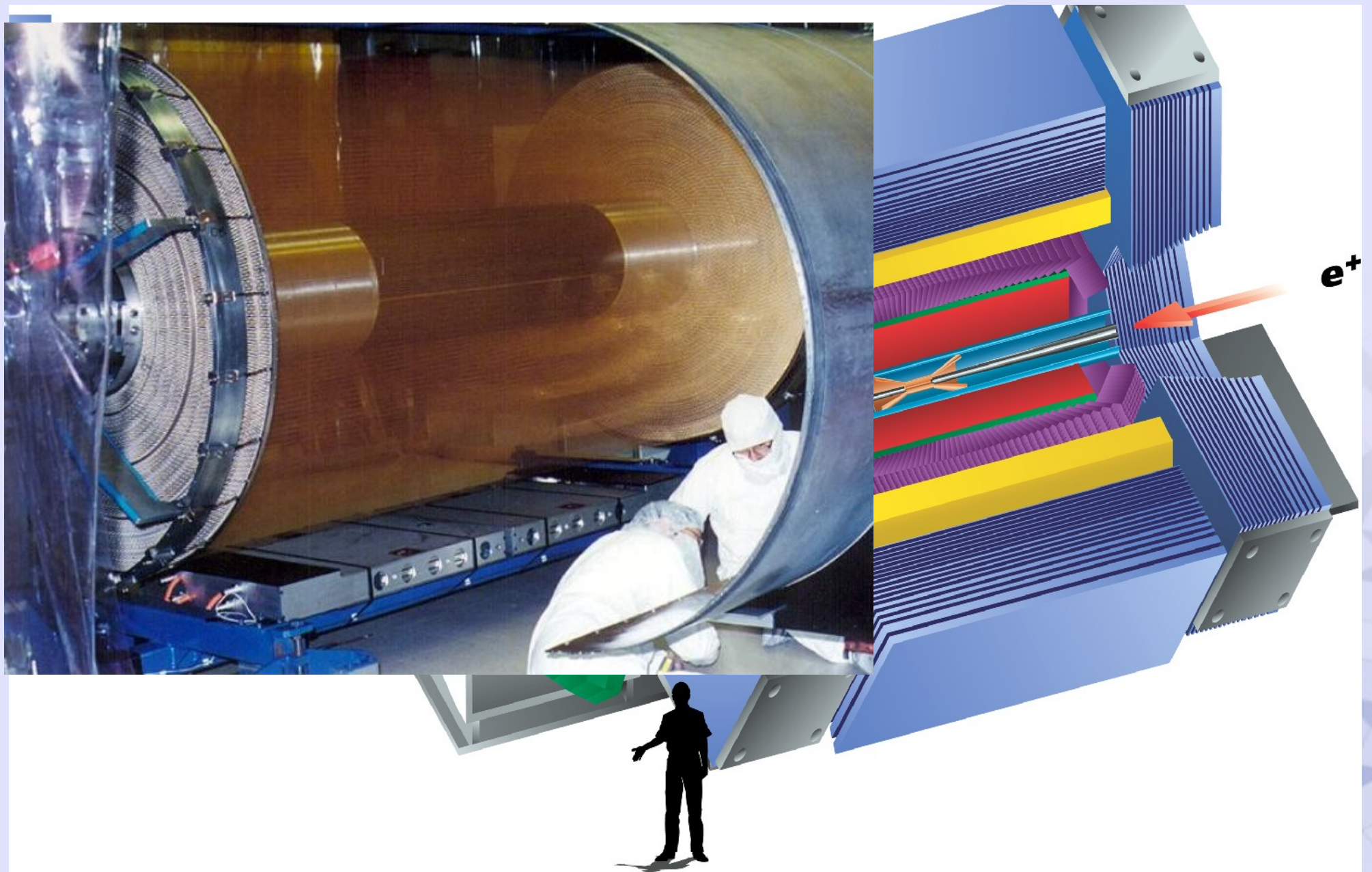


5 layer double sided  
silicon strip detector



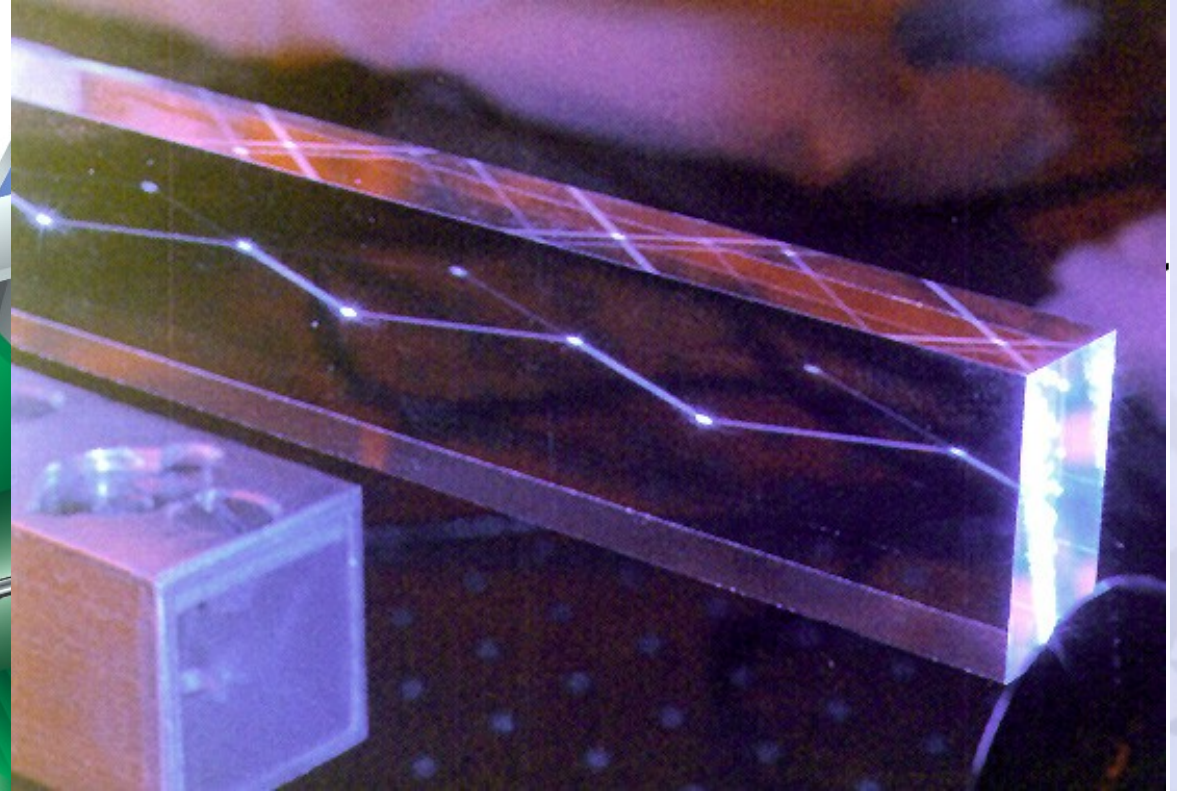
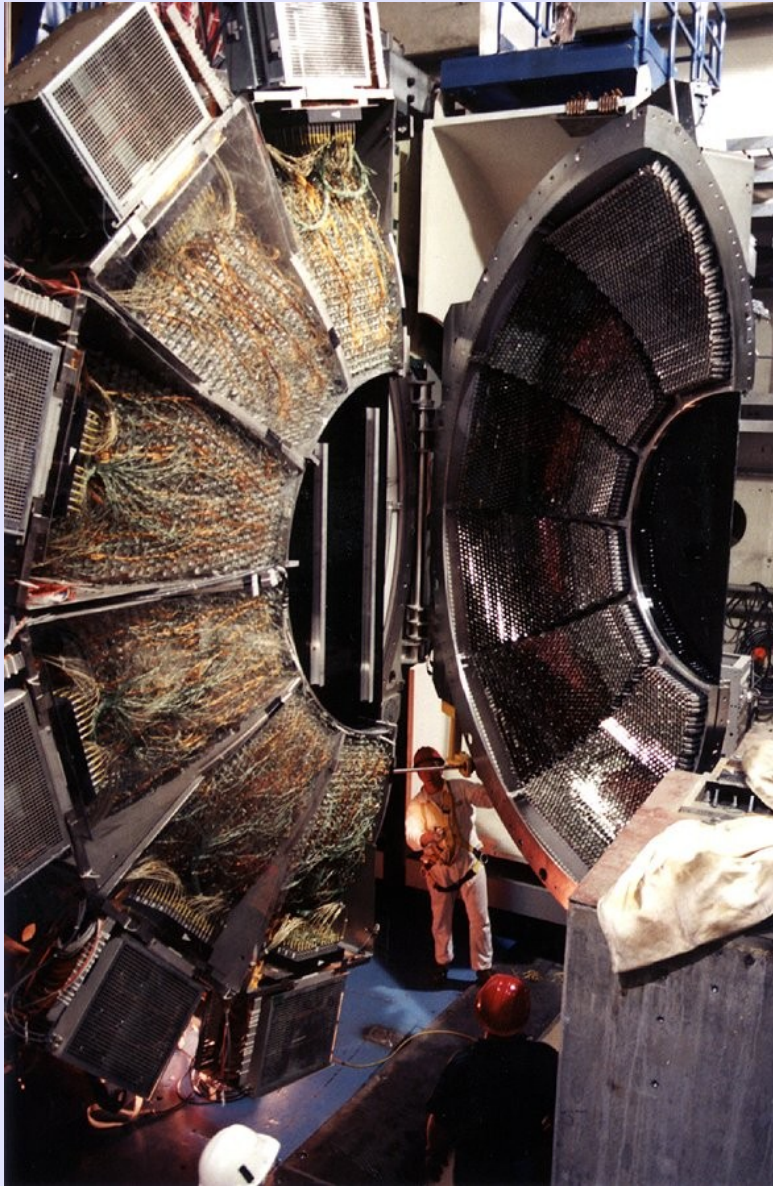


# The Drift Chamber



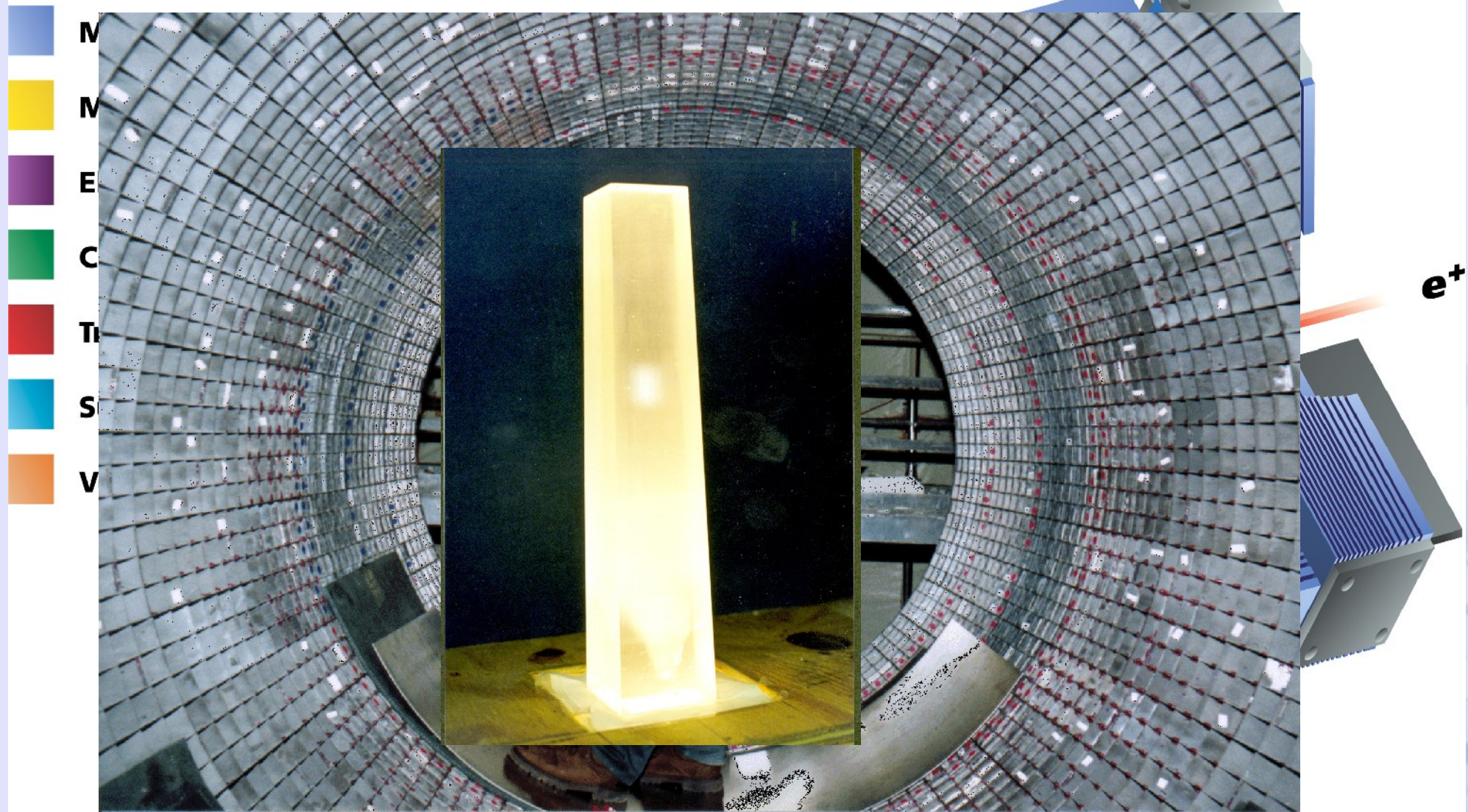


# The Detector of Internally Reflected Cherenkov Radiation





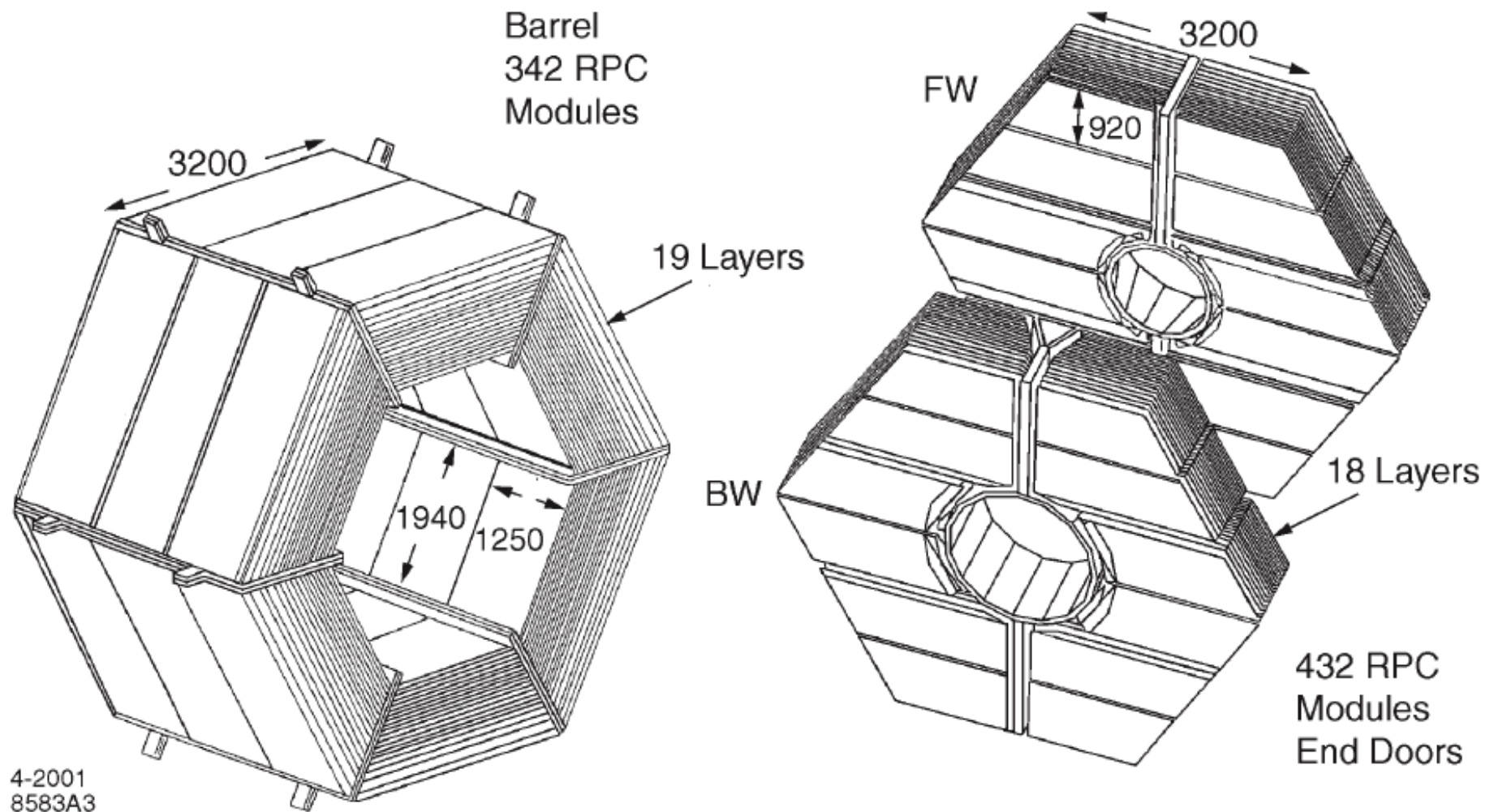
# The Electromagnetic Calorimeter



6500 CsI Crystals



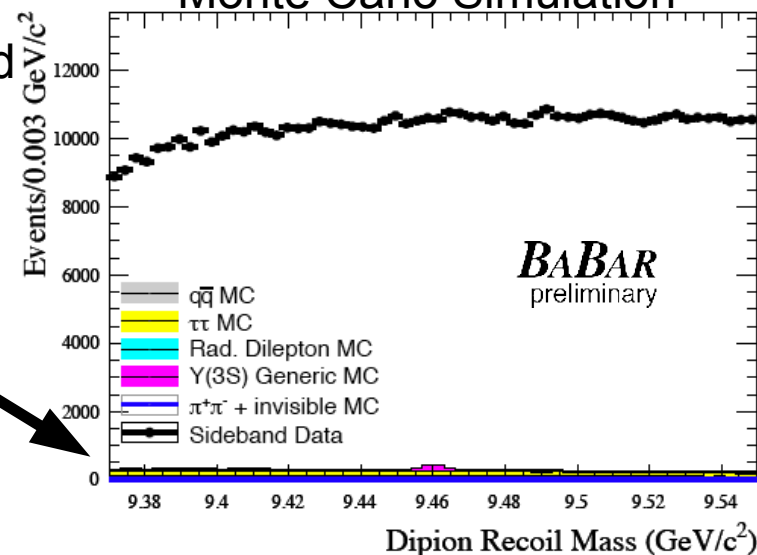
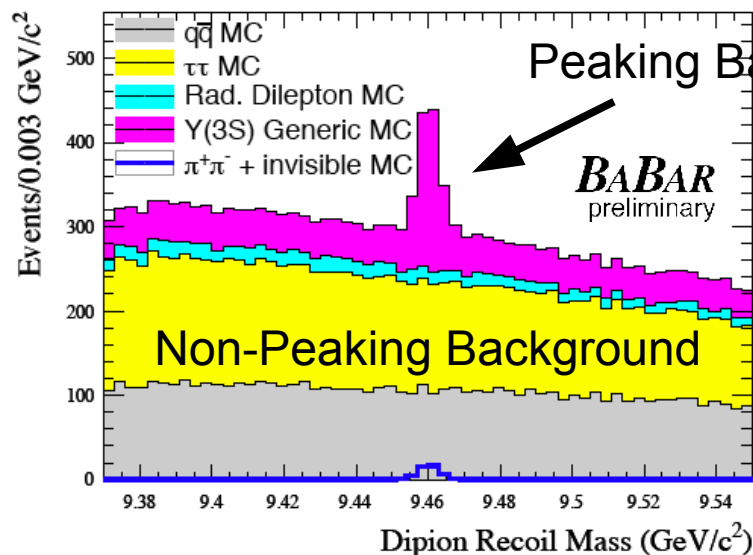
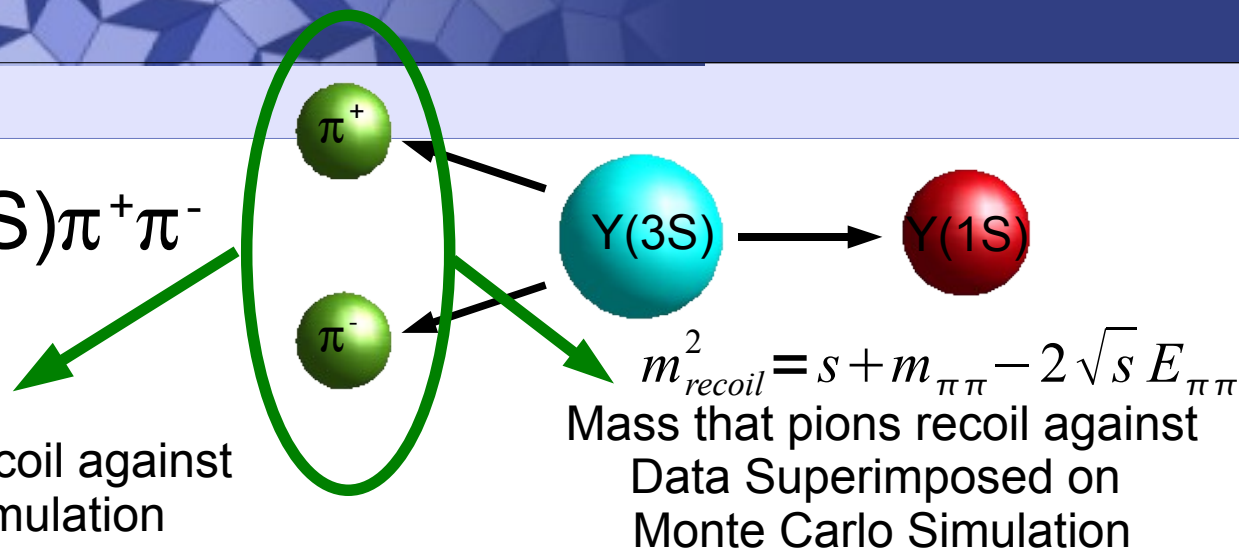
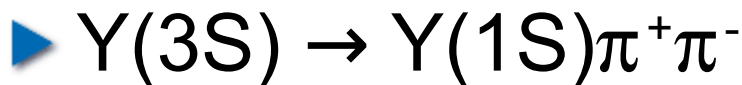
# The Instrumented Flux Return Detector



# Analysis Overview

- ▶ Identifying  $Y(1S)$  candidates
- ▶ Identifying potential backgrounds to the measurement
- ▶ Measurement of the signal
- ▶ Finding the recoil mass shape
- ▶ Systematic Errors

# Tag Analysis on Presence of Pions



- Two Different types of backgrounds – peaking and non-peaking
- Most of the data excess comes from poorly modeled photon photon fusion events



# Data Samples for this Analysis

- ▶ Looking at various data samples allows us to perform this measurement

*“There are known knowns. There are things we know that we know. There are known unknowns. That is to say, there are things that we now know we don’t know. But there are also unknown unknowns. There are things we do not know we don’t know” -Donald Rumsfeld*

- ▶ Detectable  $Y(1S)$  Decay

- 2 Lepton Collection
- 1 Lepton Collection

- ▶ Undetectable  $Y(1S)$  Decay

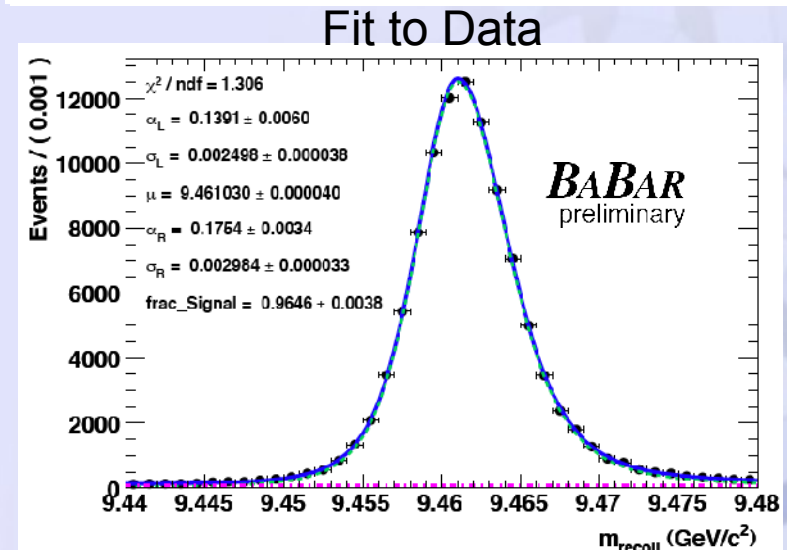
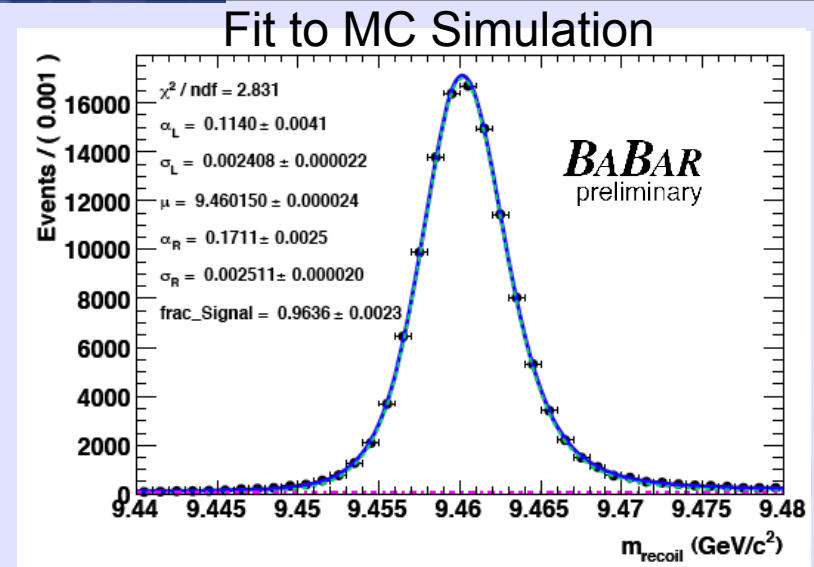
- On Peak Collection
- Off Peak Collection

# Using Visible Data to Determine Signal Shape

## “Known Knowns”

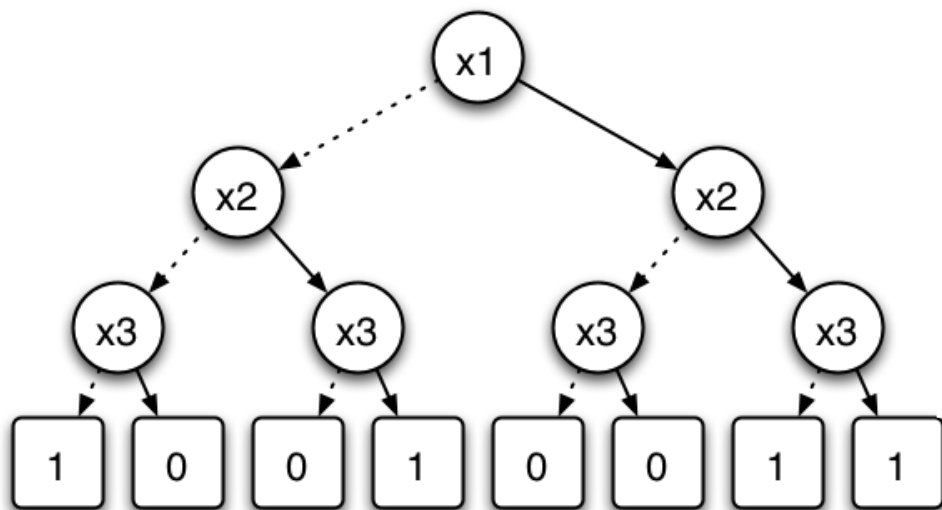
- ▶ We want the shape of the dipion recoil mass spectrum
- ▶ We gather data with 4 tracks: 2 soft tracks from pions and 2 hard tracks from  $Y(1S) \rightarrow l^+l^-$
- ▶ We fit a “Cruiff” function plus a linear function to this to find a signal shape

$$C(m_{recoil}; \mu, \alpha_L, \sigma_L, \alpha_R, \sigma_R) = \frac{1}{N} \begin{cases} \exp[-(m_{recoil} - \mu)^2 / (2\sigma_L^2 + \alpha_L(m_{recoil} - \mu)^2)], & m_{recoil} < \mu; \\ \exp[-(m_{recoil} - \mu)^2 / (2\sigma_R^2 + \alpha_R(m_{recoil} - \mu)^2)], & m_{recoil} > \mu. \end{cases}$$



# Multivariate Discrimination Algorithm Random Forest (MVA)

## ► Decision Tree

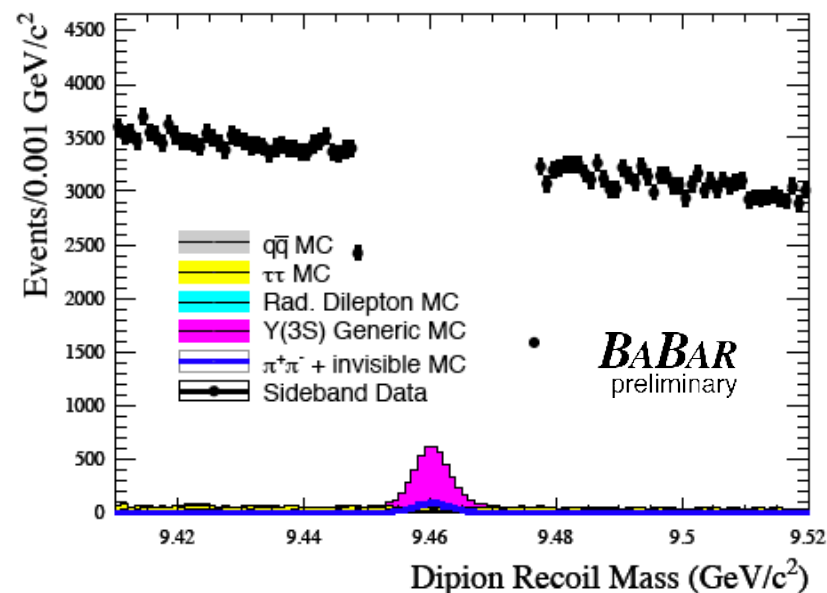


## ► Random Forest of Decision Trees

- Random ordering of inputs in many trees
- final output weighted average of these

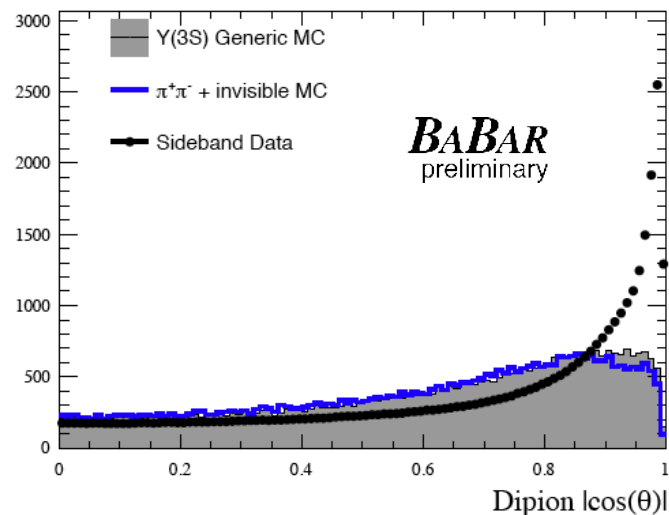
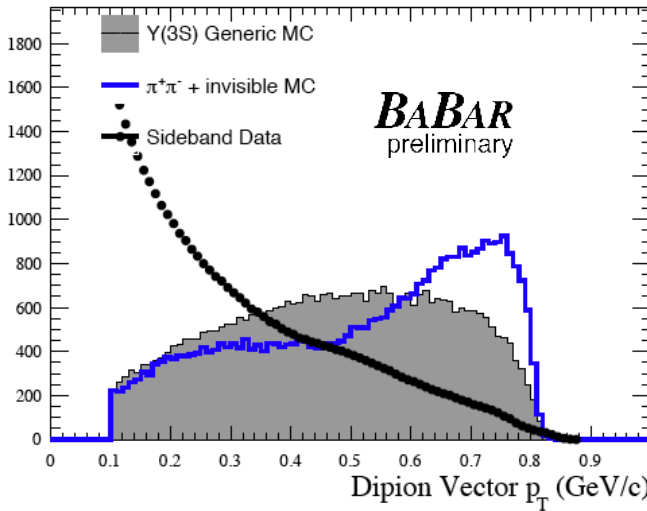
## ► Training our Random Forest

- Sideband Data as background
- Signal Monte Carlo simulation



# Choosing MVA Inputs

- ▶ Need information that can discriminate between signal and background events
- ▶ The final MVA output must be uncorrelated with dipion recoil mass
- ▶ Train the algorithm on sideband data as the background and Monte Carlo simulation of the signal



## List of MVA Inputs:

Dipion vertex probability

$|\cos(\theta_{\pi\pi})|$

Dipion  $p_T$

Pion PID

ChargedTrack multiplicity, including the pions

EMC  $K_L^0$  multiplicity

cosine of the CM angle between the highest-momentum neutral cluster and the normal to the dipion plane

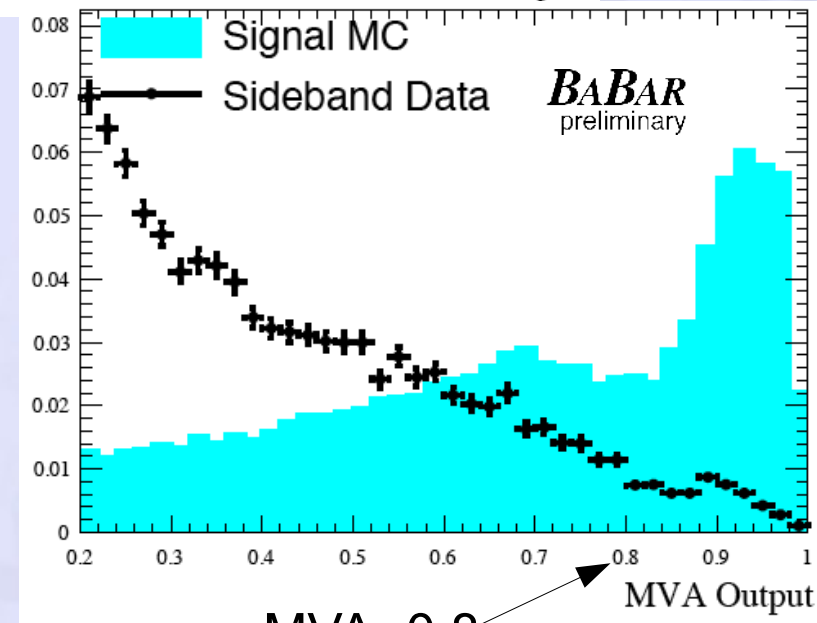
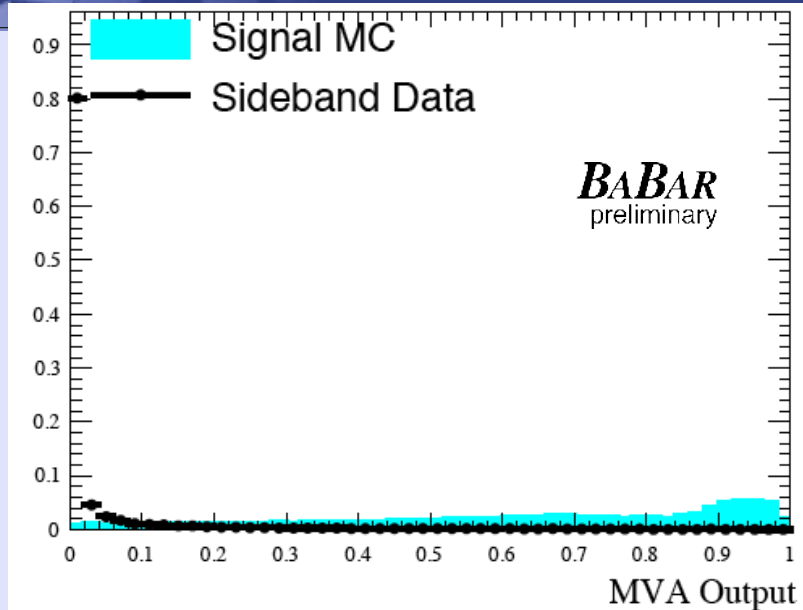
Invariant mass of the highest-momentum pair of neutral clusters

Total extra neutral energy in the CM frame

CM Energy of the highest-energy neutral cluster

# MVA Output

- ▶ Want to discriminate between a signal and backgrounds without using the recoil mass of the dipion system
- ▶ Construct a decision tree random forest algorithm to differentiate between signal and background events
- ▶ Choose MVA cut to maximize figure of merit and minimize upper limit on measurement

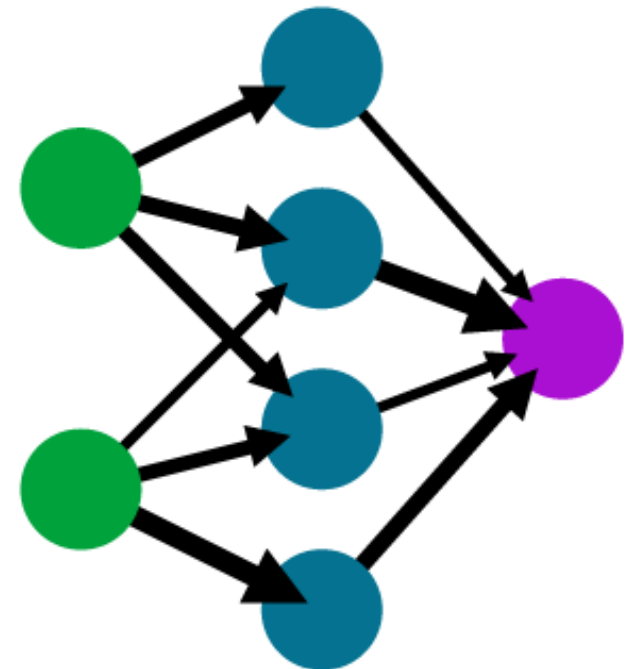


MVA=0.8  
Chosen



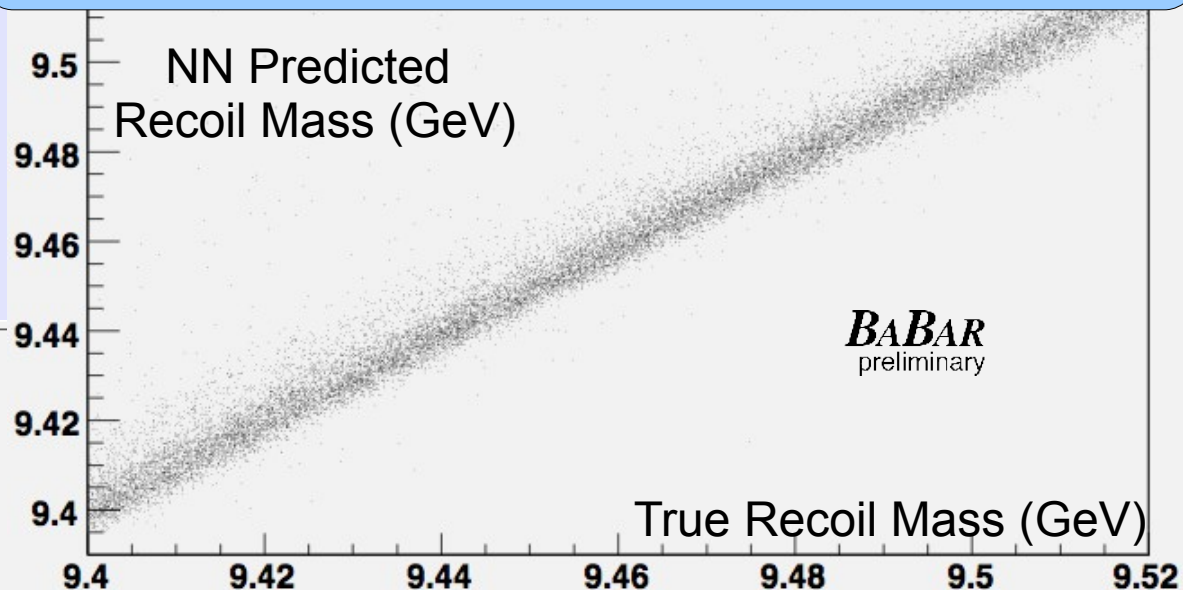
# Confirming MVA Not Correlated with Dipion Recoil Mass

- ▶ All the MVA inputs are individually uncorrelated with dipion recoil mass
- ▶ Want to make sure that no function of the inputs can predict recoil mass
- ▶ Use a Neural Net
  - Inputs from MVA
  - Train on  $m_{\text{recoil}}$

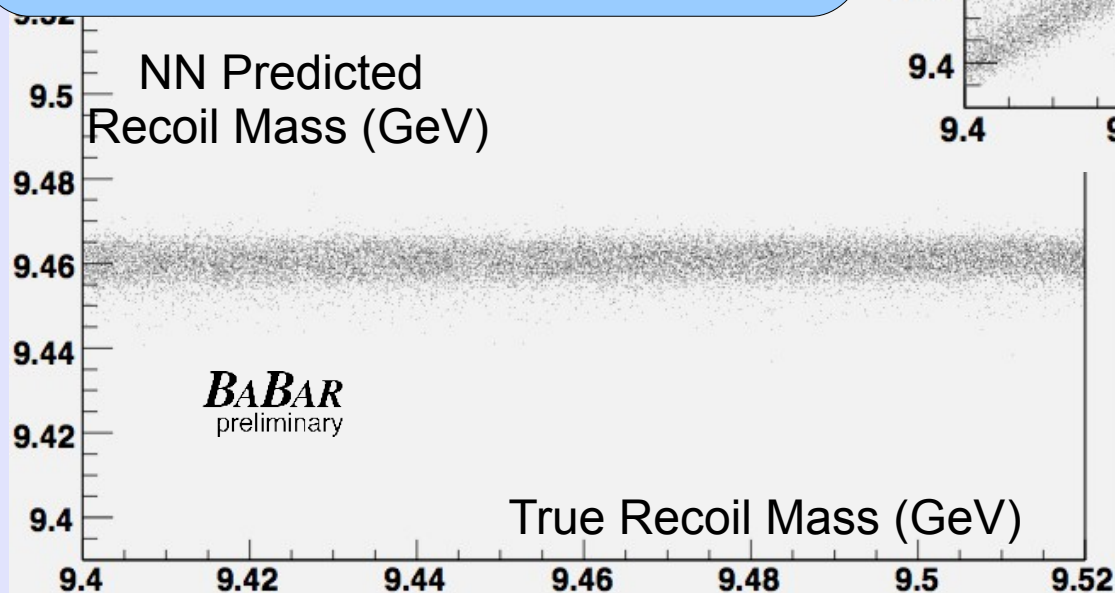


# Neural Net Correlations with Recoil Mass

Giving the Neural Net the additional information of the two pion momenta from the dipion system allows it to predict the dipion recoil mass quite well



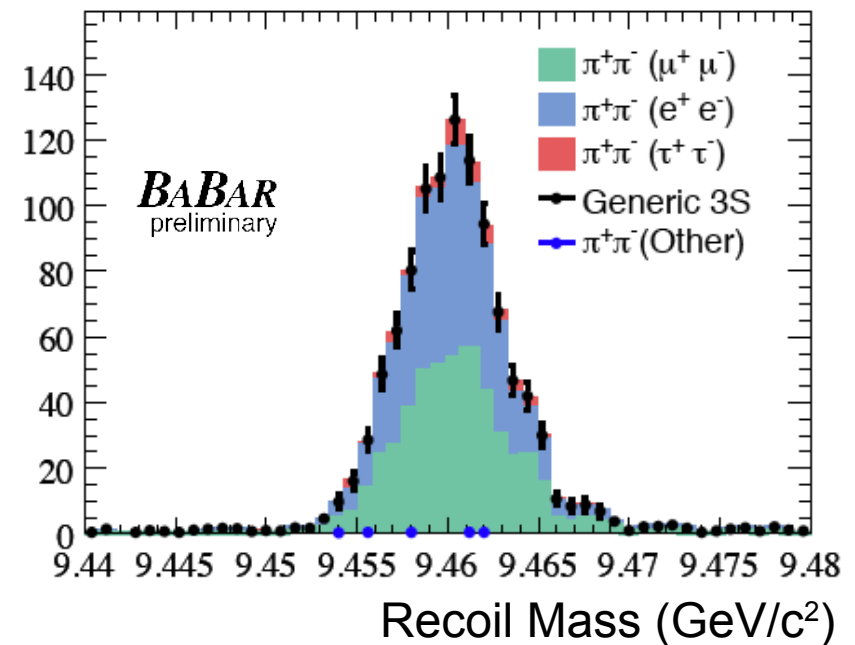
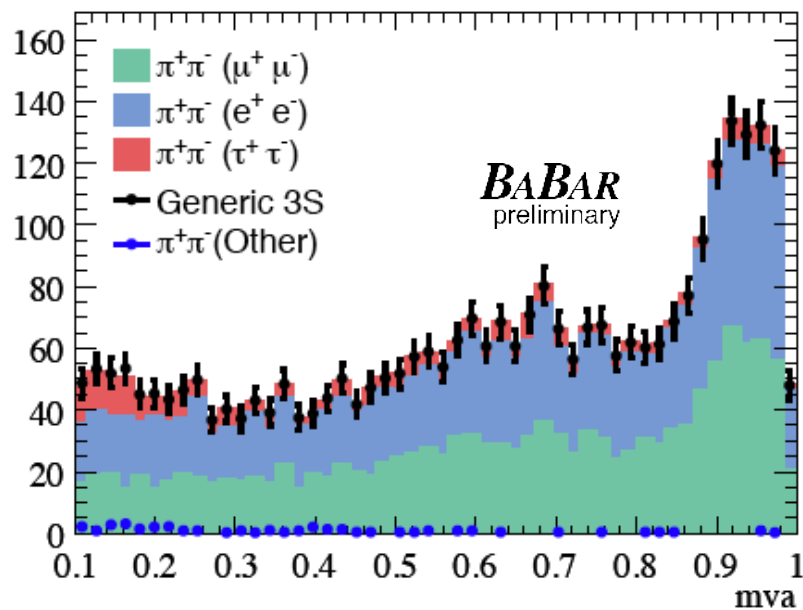
Training a Neural Net on the same inputs as the MVA but using the recoil mass of the dipion as the output results in an uncorrelated NN output



# Expected Undetected Decays

## “Known Unknowns”

- ▶ We expect some decays of the  $Y(1S)$  to go undetected because of the non-hermeticity of the detector
- ▶ Almost all (99.8%) of these come from  $Y(1S) \rightarrow l^+l^-$  in the case that the leptons escape down the beam pipe

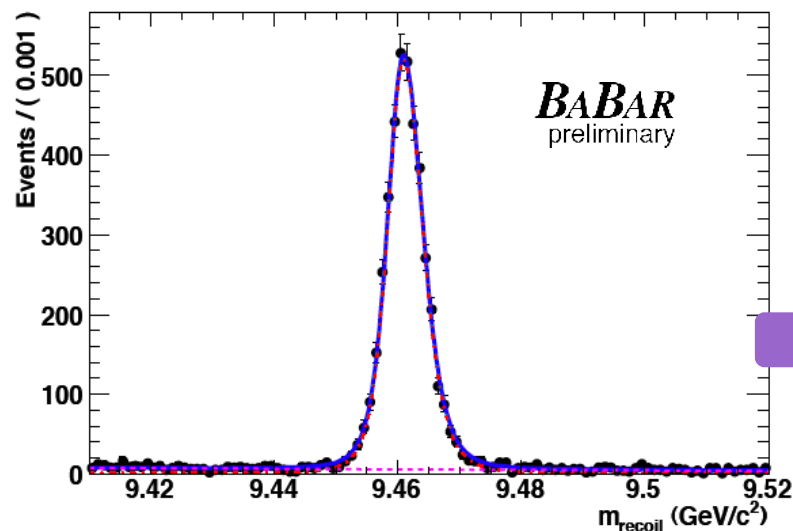


# Using Visible Data to Calibrate the Monte Carlo Simulation

- ▶ In addition to the 2 lepton sample used to measure the signal shape, we also collect a 1 lepton sample
- ▶ Use this sample to assess the accuracy of the simulation in angular distribution of the lepton decays, allowing calculation of undetected decays

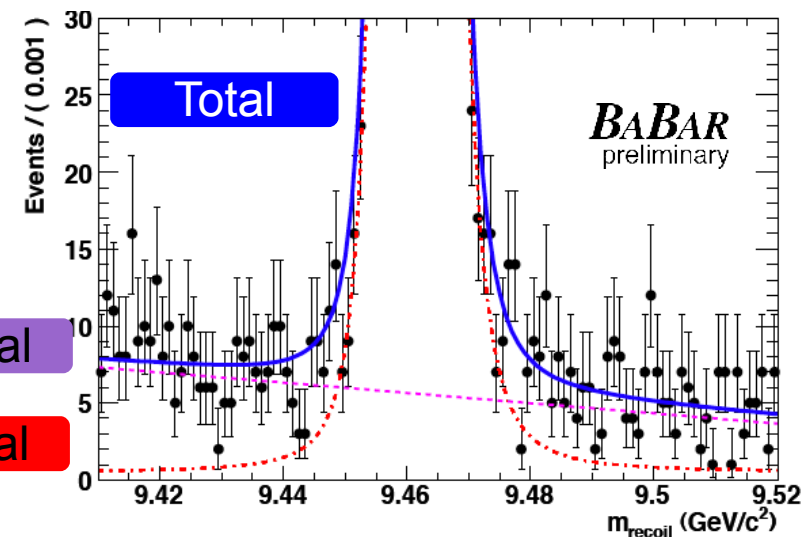
Dipion Recoil Mass of 1 Lepton Sample

Zoom



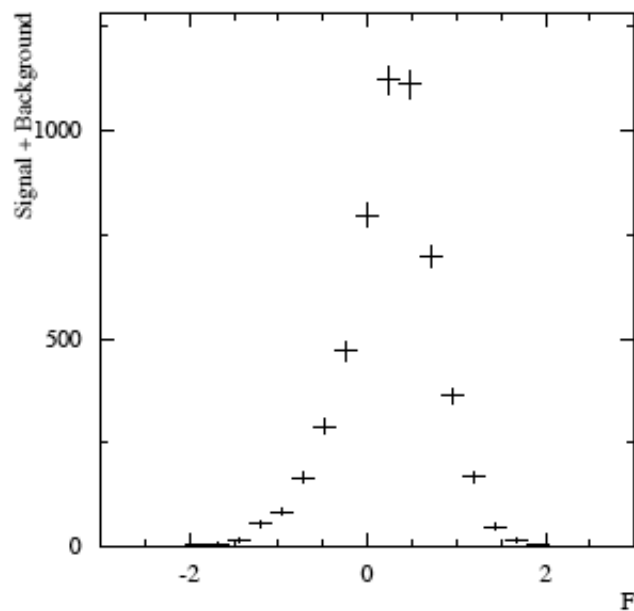
Non-Signal

Signal



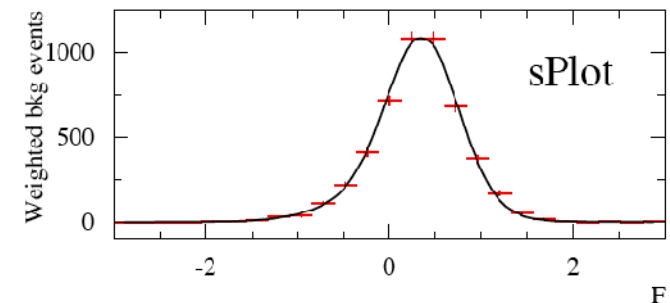
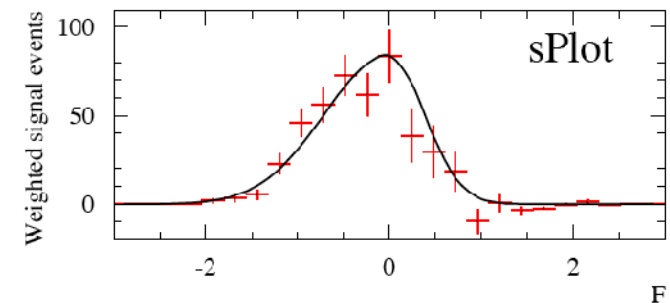
# Aside: sPlots<sup>1</sup> – Projecting a Pure Signal from a Fit

- ▶ We want to compare our Monte Carlo simulation of  $Y(1S) \rightarrow l^+l^-$  with the actual data, which incorporates a component that does not come from this process
- ▶ We appeal to a technique known as sPlots:



Signal

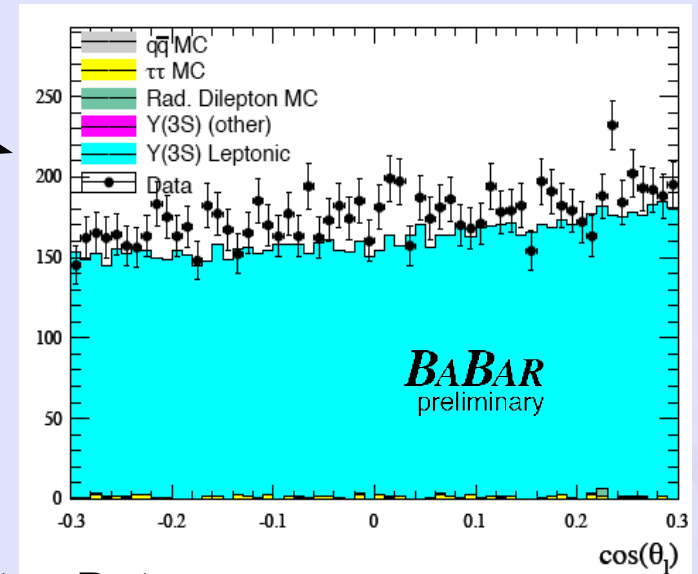
Background



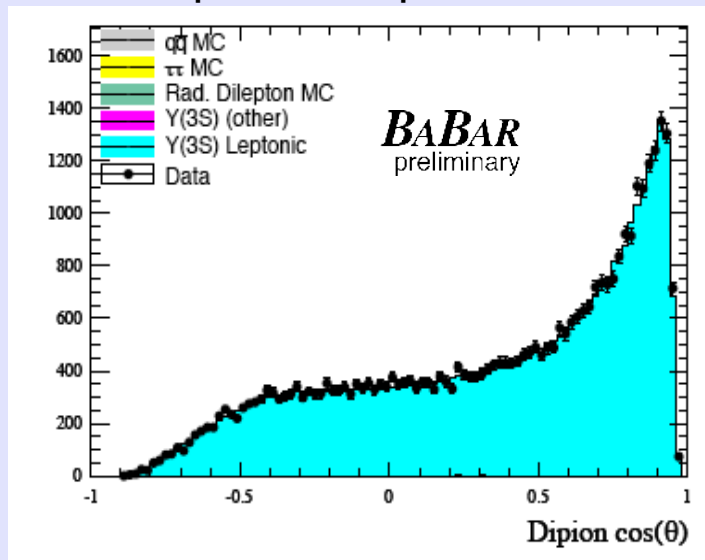


# Correcting the Simulation with Control Data

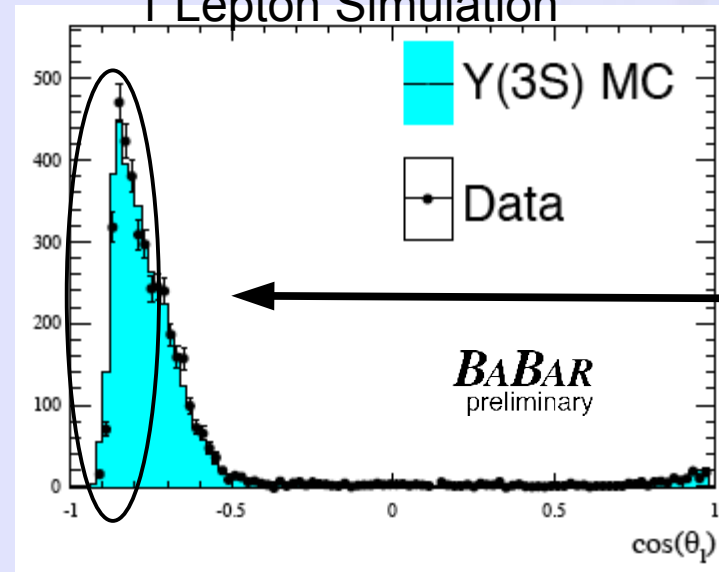
- Use 2 Lepton Data Sample in a restricted range of the detector to calculate a correction factor for the yield of the simulation
- Apply this correction factor to both the 1 and 2 Lepton simulated datasets and compare with the Data



2 Lepton Samples



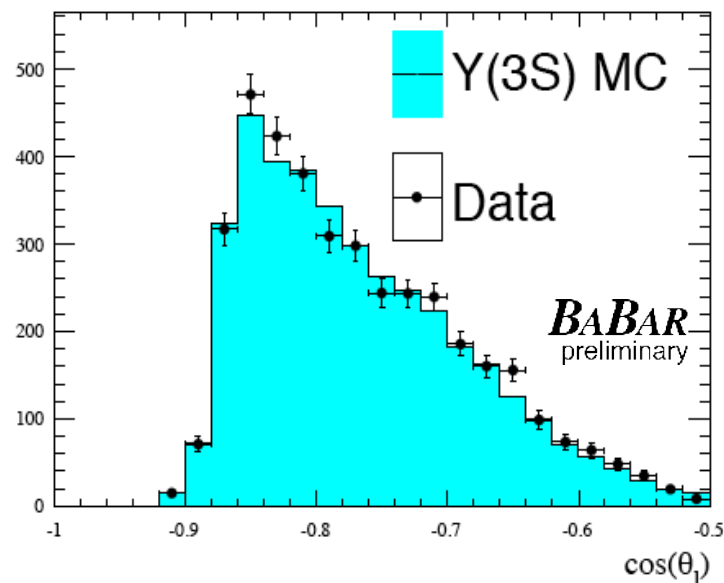
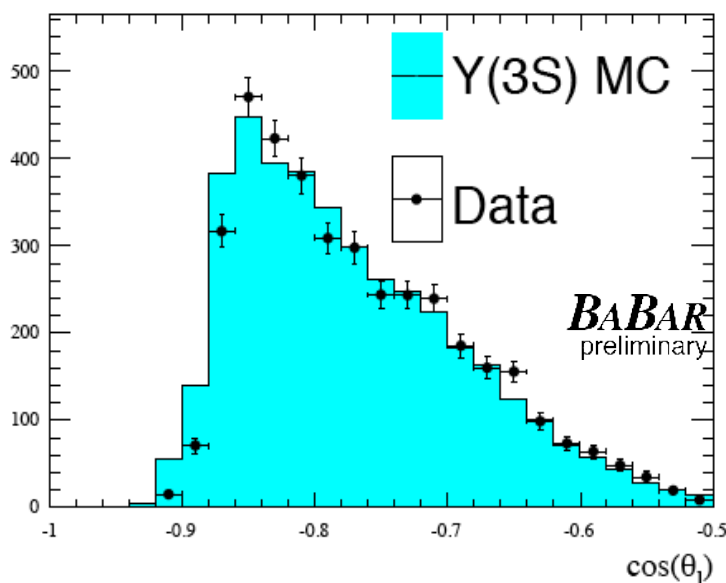
sPlot of 1 Lepton Data,  
1 Lepton Simulation



Difference Seen  
at edge of  
detector

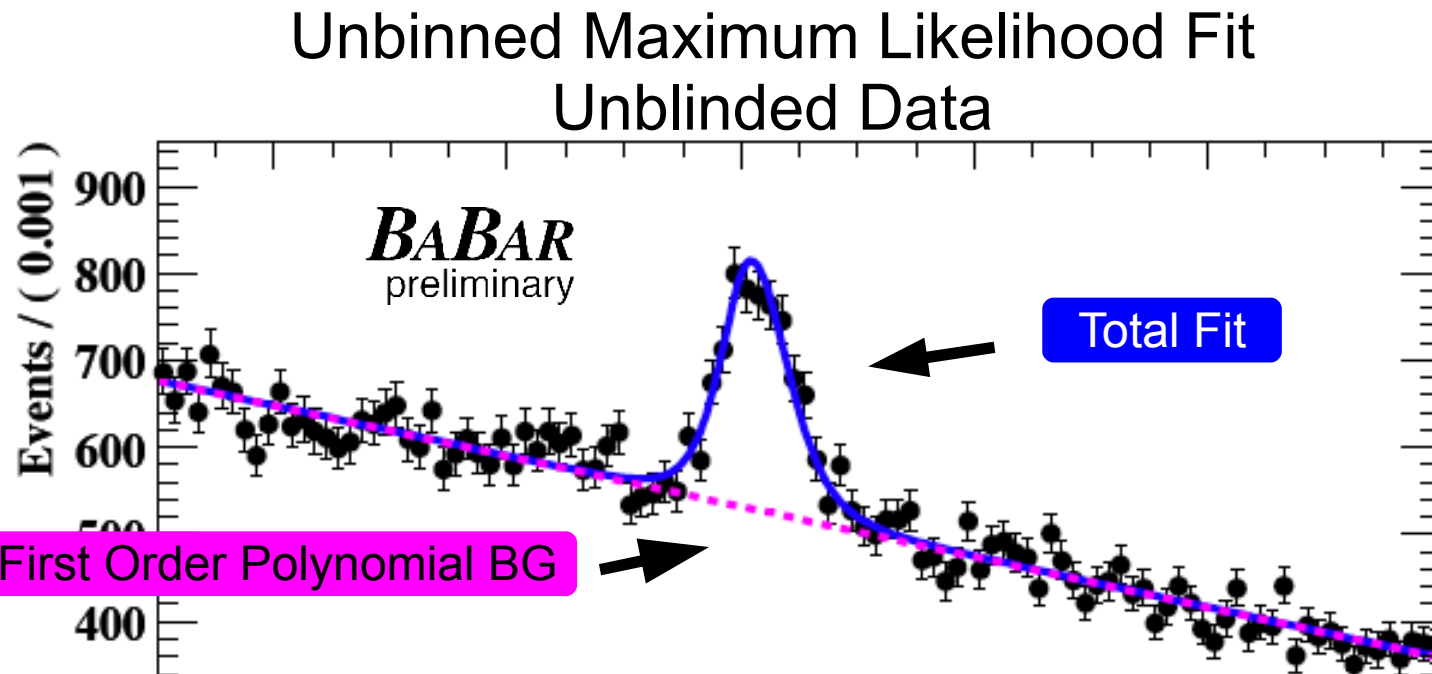
# Correcting 1 Lepton Simulation

- ▶ Use a “killing” procedure on simulation at edge of detector to align with data
- ▶ Events that are killed are added to the undetected simulation, correcting the expected number of undetectable events



- ▶ Use corrected simulation and killed events calculate expected yield: 2301 from scaling and 169 from killing, totaling 2470 expected.

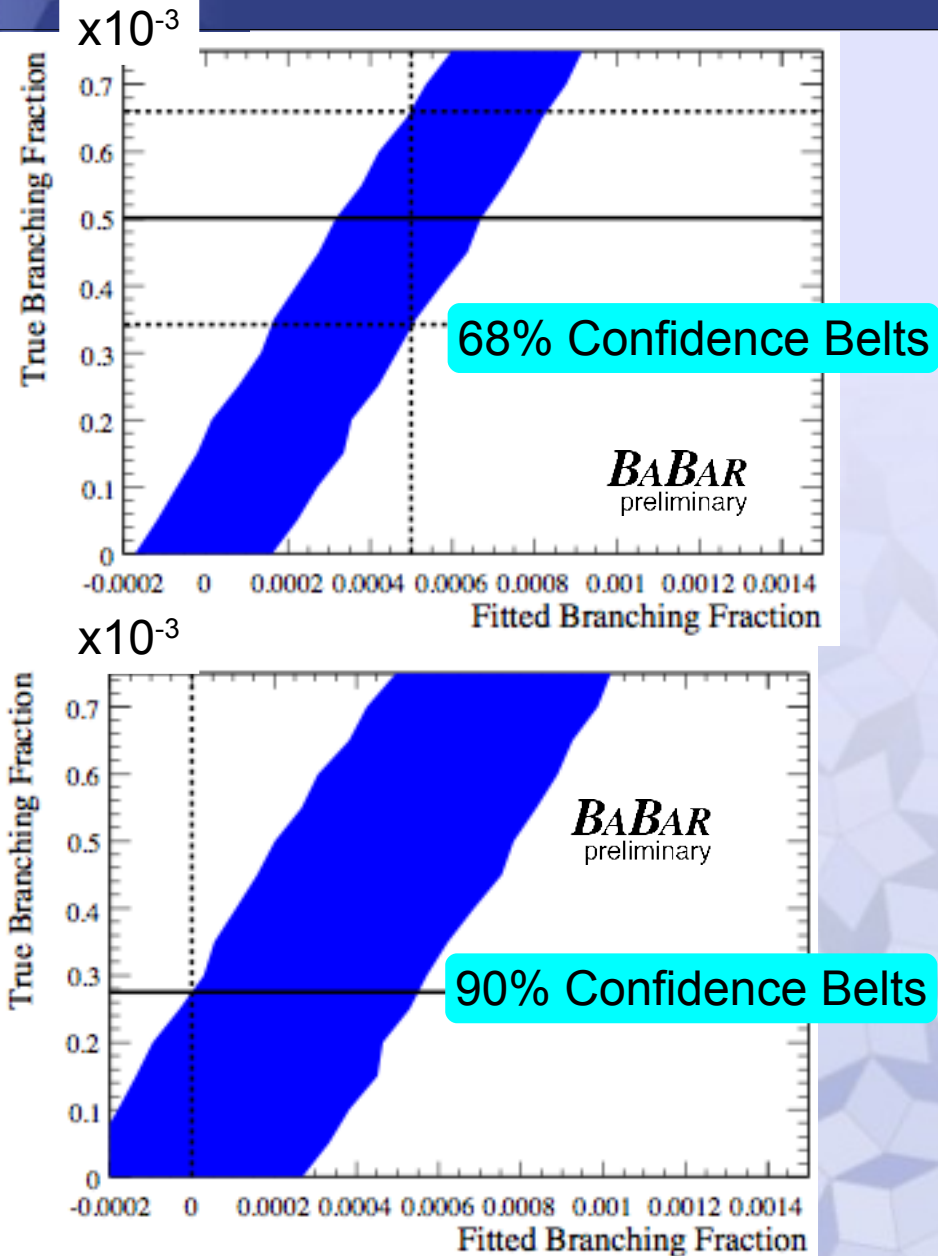
# Fitting Invisible Data Set “Unknown Unknowns”



- In order to find the signal yield, we use a Maximum Likelihood fit of three functions:
  - Use a first order polynomial background with floated yield
  - Use a Peaking Function of the fixed appropriate yield
  - Fit another Peaking Function with a floating yield
- This floating yield is the number of invisible decays

# Estimating Sensitivity

- ▶ Use method of Feldman and Cousins<sup>1</sup> to estimate sensitivity to signal
  - In the absence of signal  $BF = 0 \pm 1.6 \cdot 10^{-4}$  (stat.)
- ▶ Run “Toy Monte Carlo” Experiments with different signal hypotheses
- ▶ Calculate 90% confidence limits in the absence of a signal
  - $BF < 2.8 \cdot 10^{-4}$  [90%CL]



1. Gary J. Feldman, Robert D. Cousins Phys.Rev.D57:3873-3889,1998 arXiv:physics/9711021v2

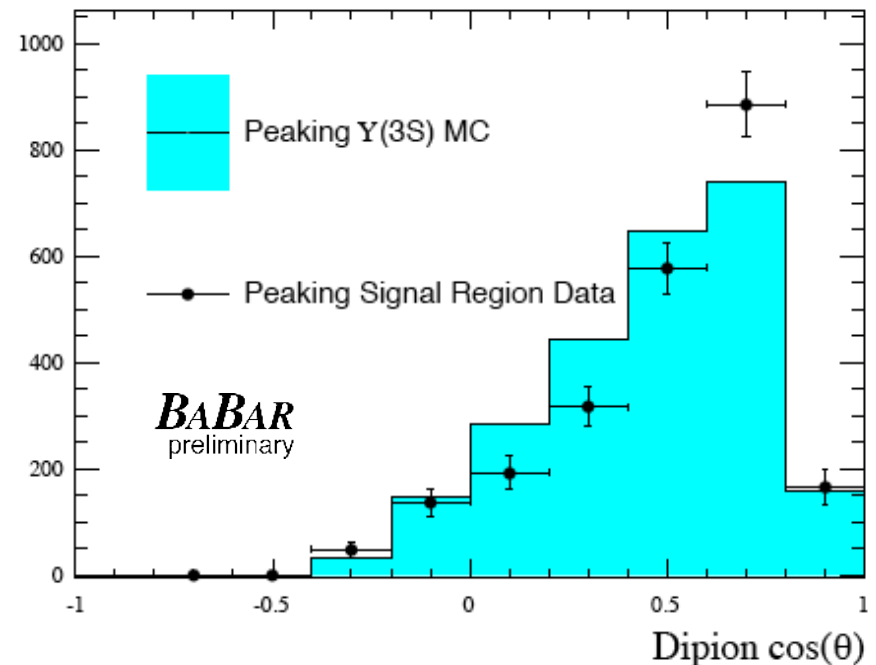
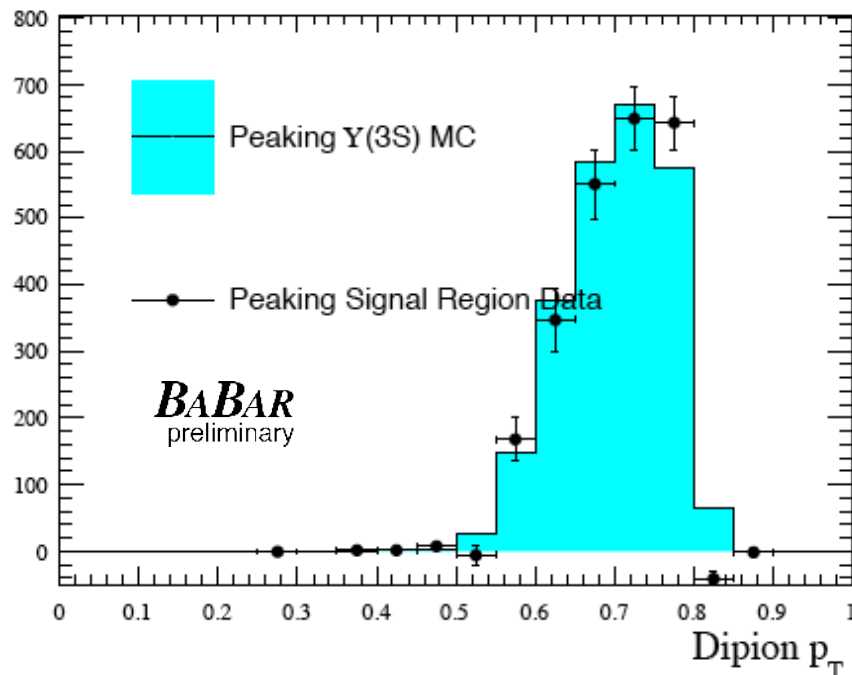
# Sources of Systematic Error

- ▶ Currently calculating systematics for this measurement
  - 2 Lepton scaling correction – 1.1%
  - 1 Lepton correction – 2.0%
  - Hadronic Peaking Backgrounds – 0.6%
  - Software Trigger – 0.9%
  - $Y(3S)$  Counting – 1.1%
- ▶ MVA systematics still under investigation



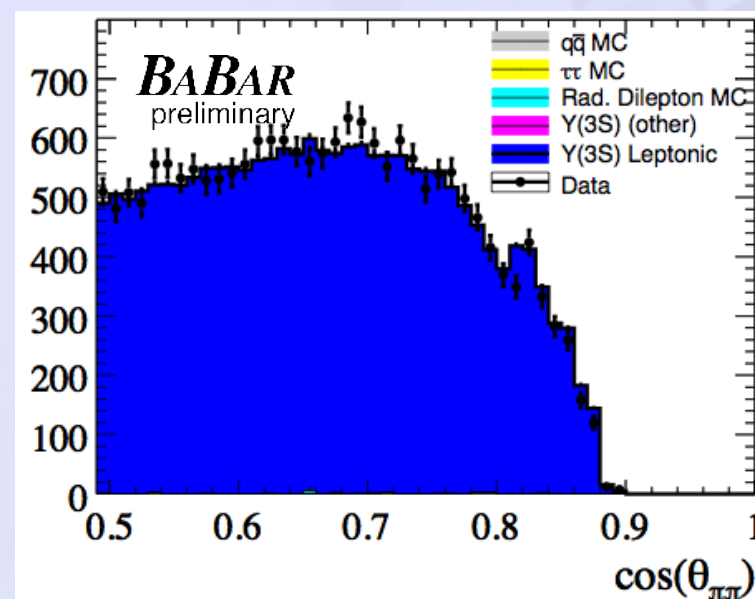
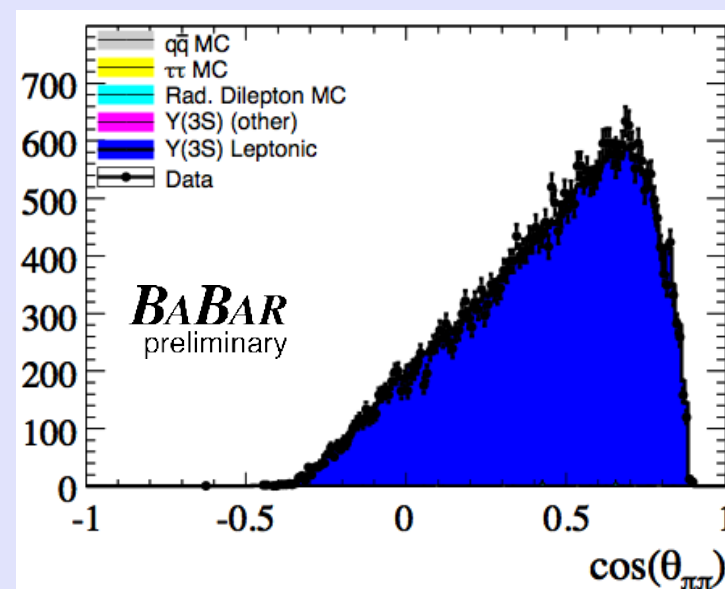
# Current State of Analysis

- ▶ Checking effects of MVA on data and simulation
- ▶ Using sPlots to project distributions of MVA inputs from invisible dataset and compare them to predictions



# Variables in 2 Lepton Control Sample

- ▶ Excellent agreement between data and Monte Carlo simulation in 2 Lepton Control Sample
- ▶ Suggests perhaps differences in the hardware trigger efficiency for the data and simulation in the 0 Lepton Sample



# Plans for this Discrepancy

- ▶ Check correlations with hardware triggers in these variables
- ▶ Look for other variables involved in the MVA that are conspiring to shift these distributions
- ▶ Look at models of dipion transition used within the Monte Carlo simulation (from CLEO<sup>1</sup>).

1. D. Cronin-Hennessy, et al Phys.Rev.D76:072001,2007 [arXiv:0706.2317v2](#)



# Preliminary Results

- ▶ After eliminating data used for training the MVA, we have 91.42 million  $Y(3S)$  events
- ▶ A signal efficiency of 16.4% and a  $BF(Y(3S) \rightarrow Y(1S)\pi^+\pi^-)$  of 4.48% giving ~67.2 thousand  $Y(1S)$  mesons
- ▶ We measure a yield of  $BF(Y(1S) \rightarrow \text{invisible})$  that is consistent with zero
- ▶ We are in the process of calculating systematics

# Conclusion

- ▶ Exciting new result from our exciting new dataset
- ▶ Hopefully, we will soon have the systematics complete and will be able to quote a new limit
  - Data set 7 times as large as previous data set
  - Upper limit estimate of  $2.8 \cdot 10^{-4}$  as opposed to previous best of  $2.5 \cdot 10^{-3}$
  - Will constrain NMSSM predictions that go up to  $4.2 \cdot 10^{-4}$
- ▶ The systematic error estimation is still ongoing
  - Analysis still in progress and undergoing internal review

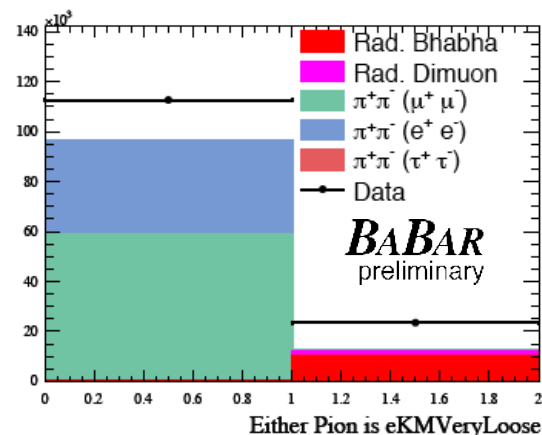
# Backup Slides



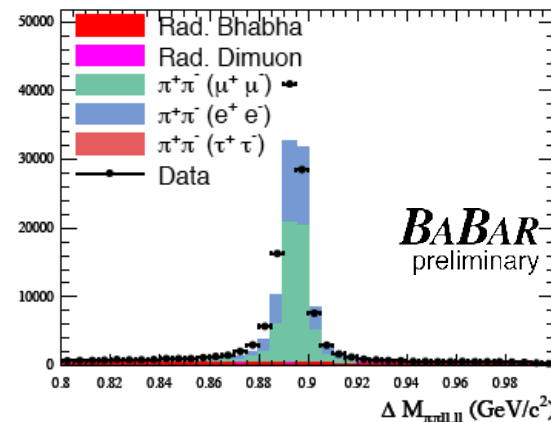
# Unparticles

- ▶ Unparticles and  $Y(1S) \rightarrow$  “invisible” +  $\square$
- ▶ Allows identification of mass resonances or a continuous mass spectrum, differentiating between standard particles or unparticles

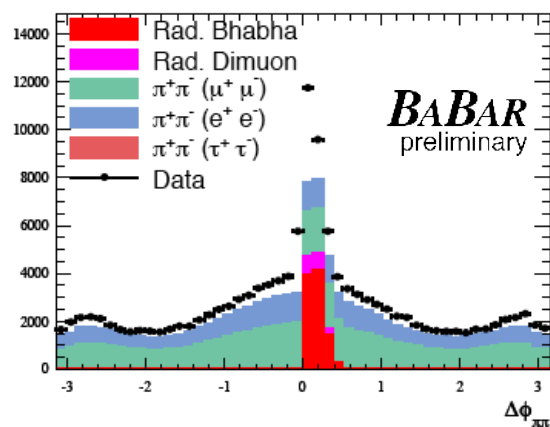
# Removing Radiative Dilepton Background



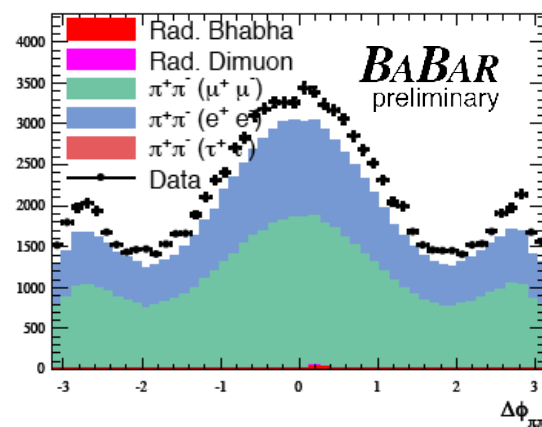
(a) A binary output, requiring either pion pass eK MVeryLoose



(b) The mass difference between the reconstructed  $T(3S)$  and  $T(1S)$

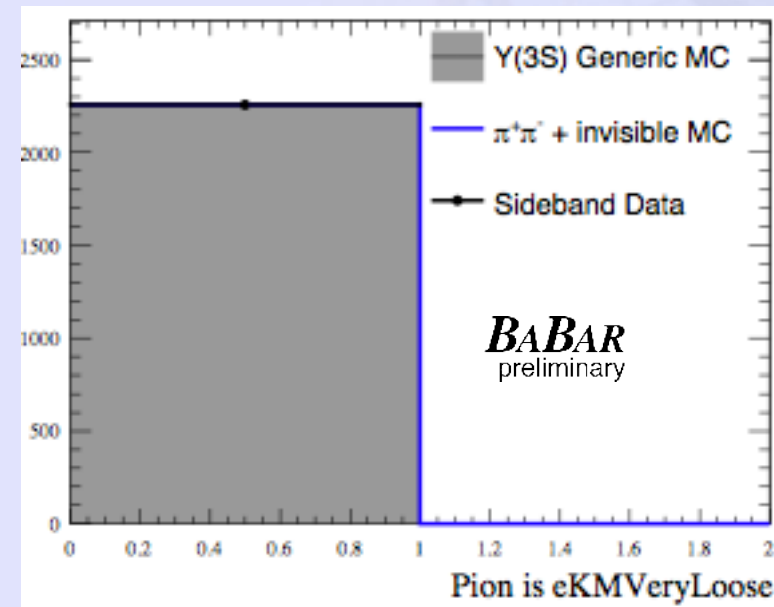
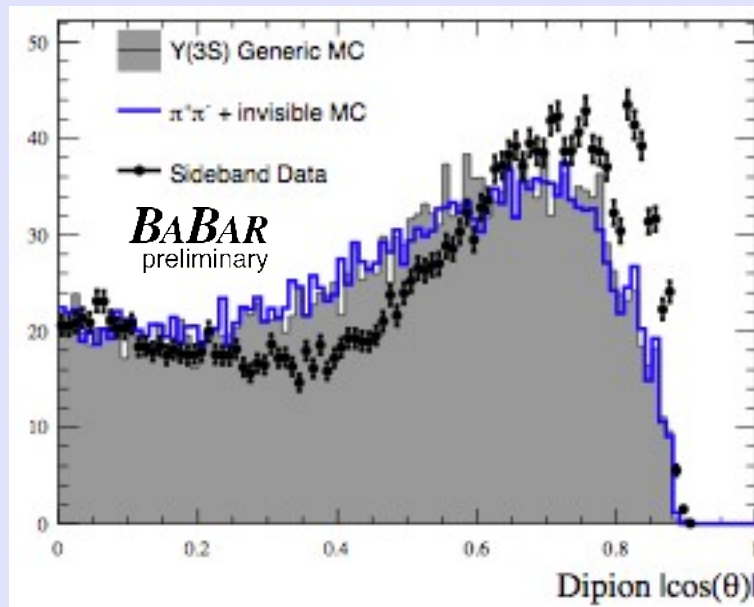
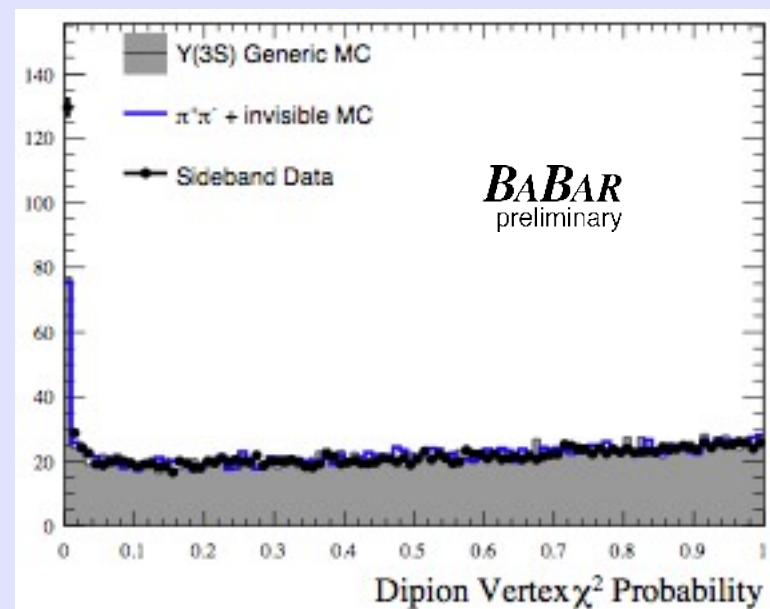
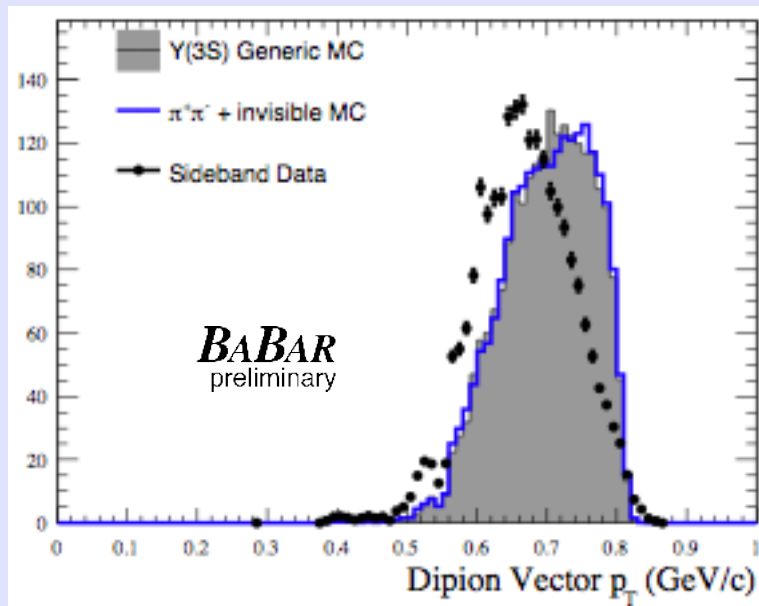


(c) The opening angle between the pions in the plane transverse to the z-axis



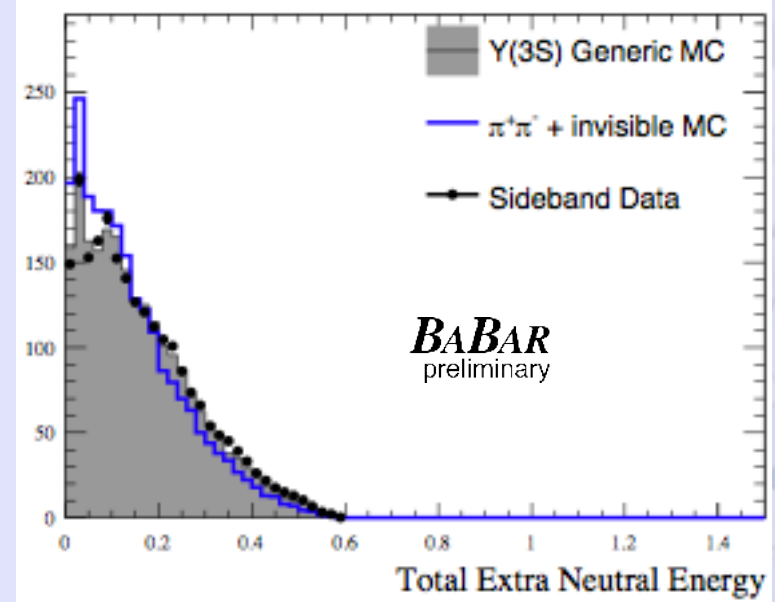
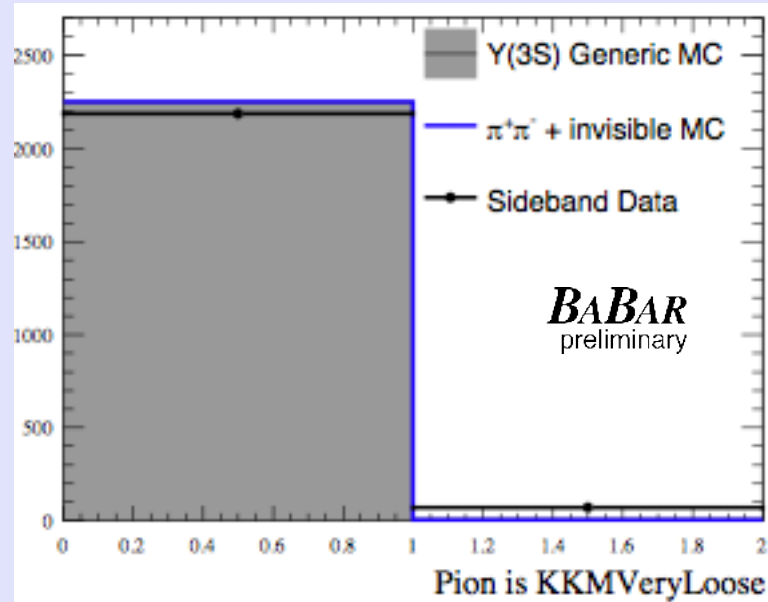
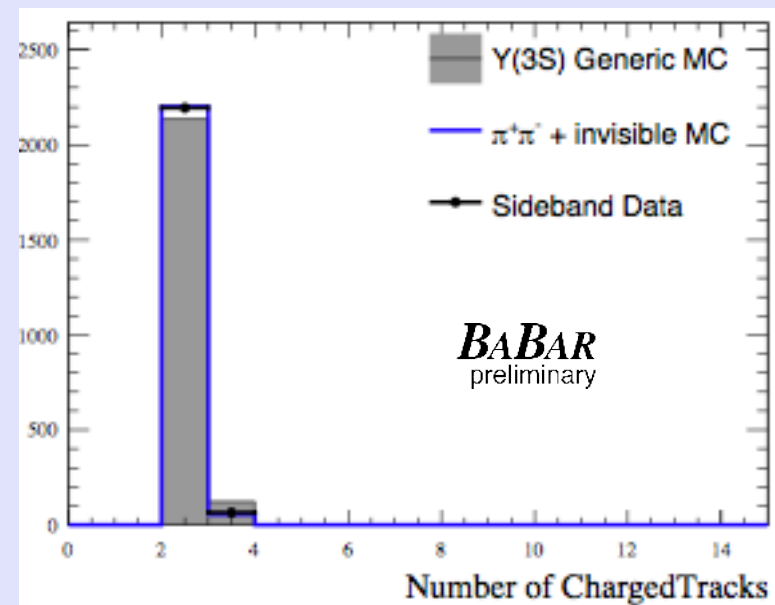
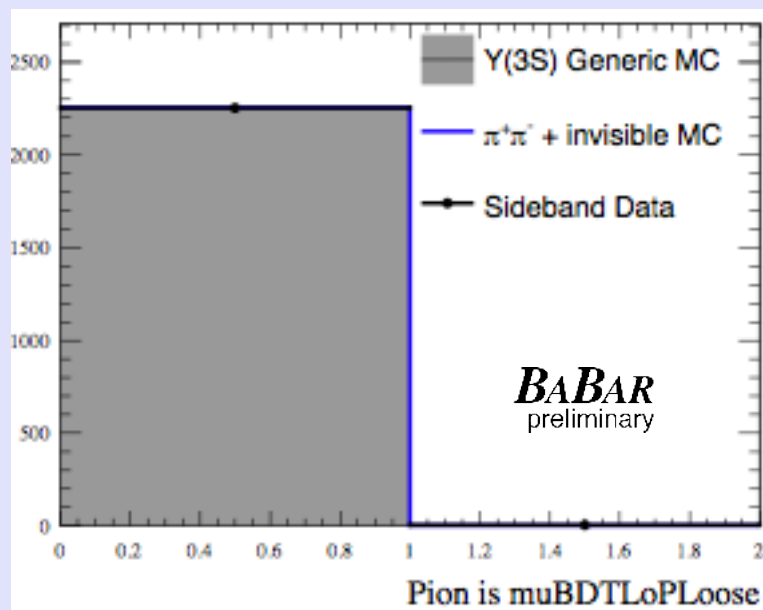
(d) The opening angle between the pions in the plane transverse to the z-axis, after cuts on electron ID and the mass difference

# MVA Inputs

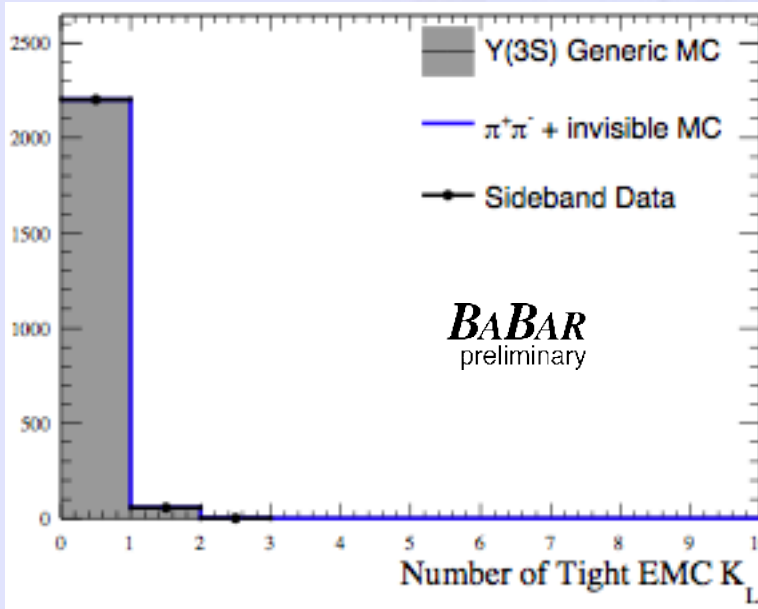
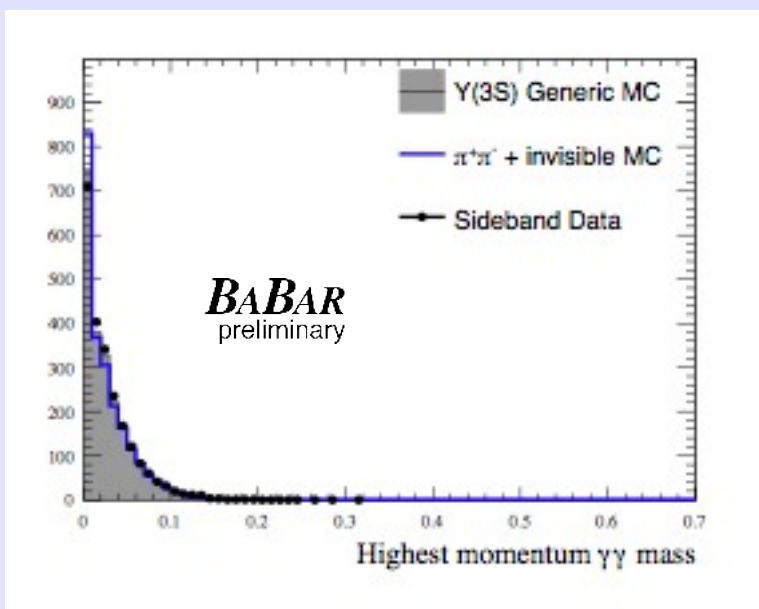
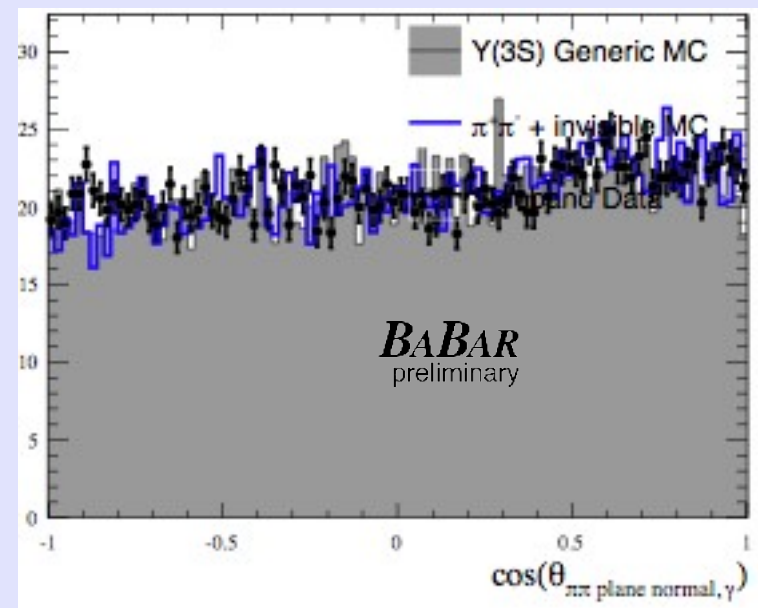
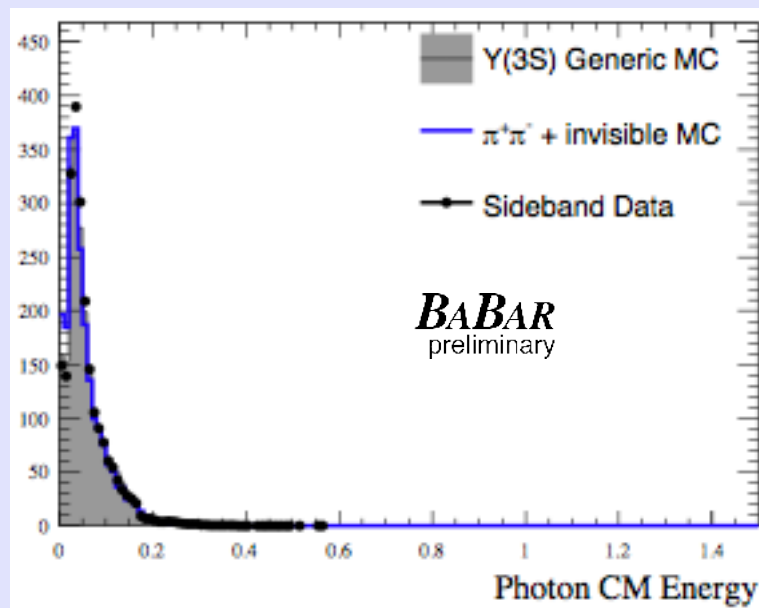




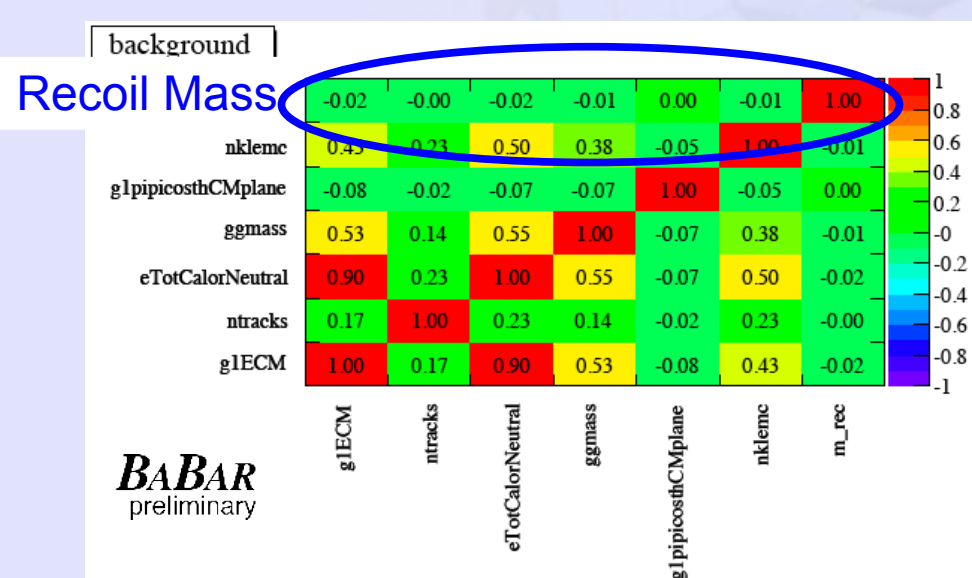
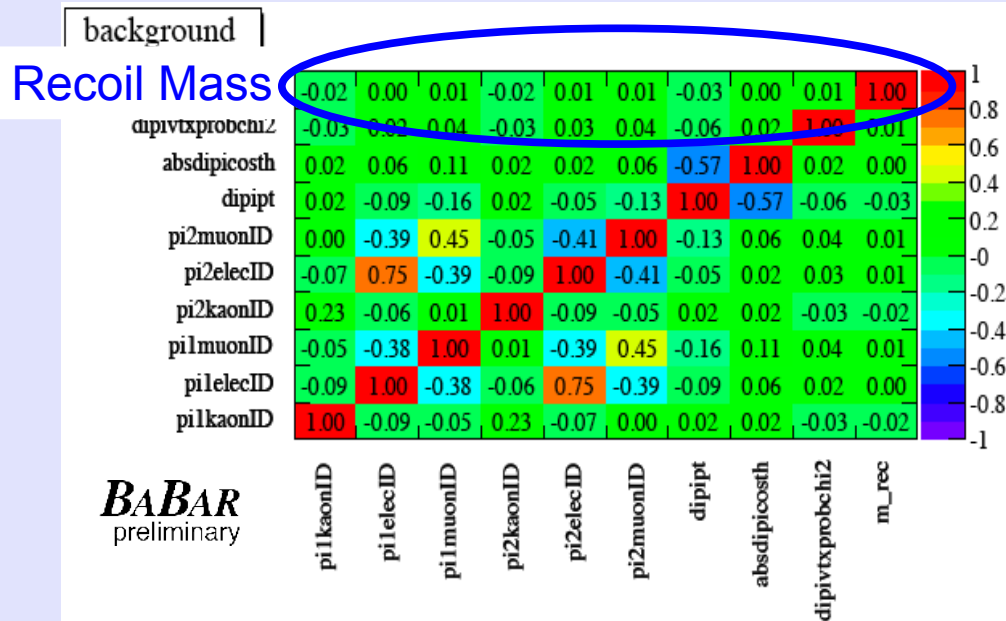
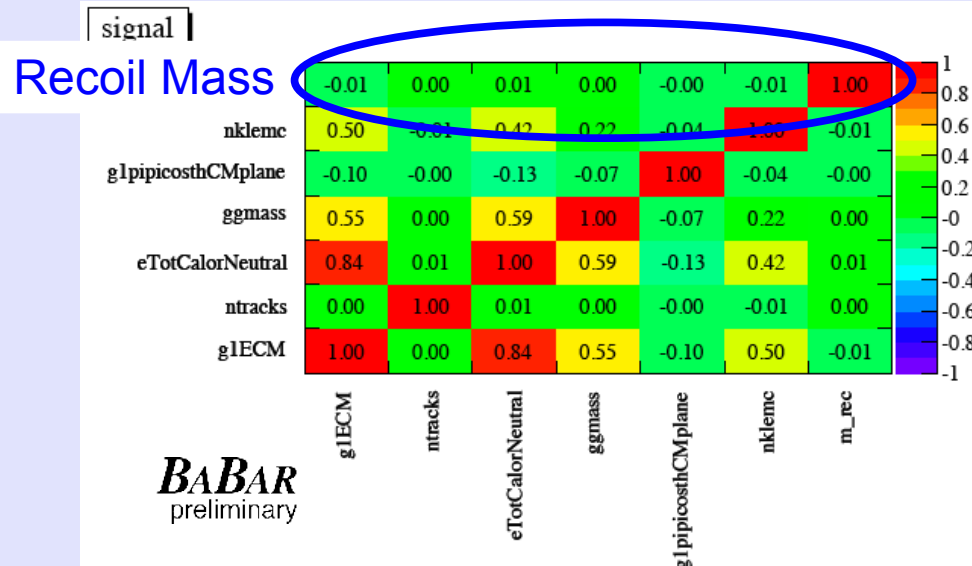
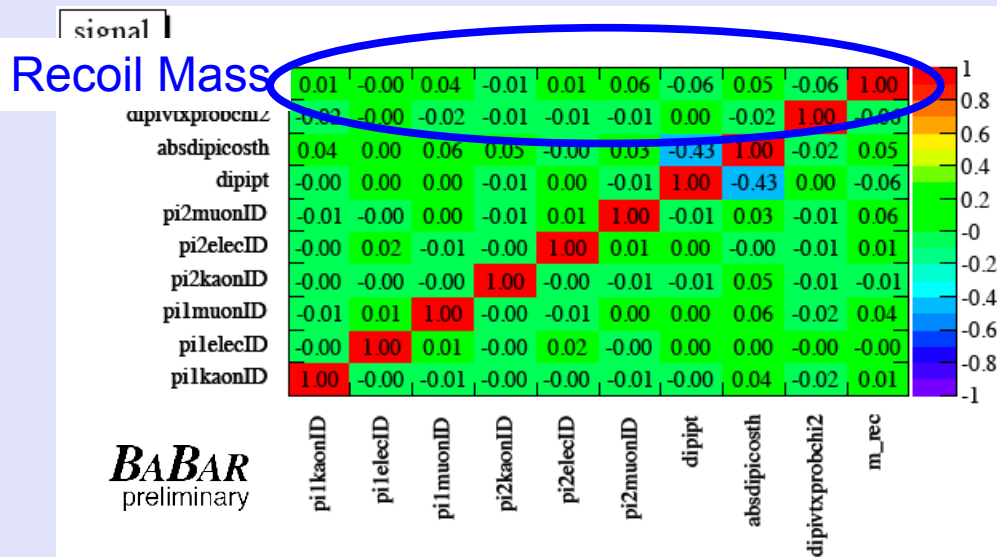
# MVA Inputs



# MVA Inputs



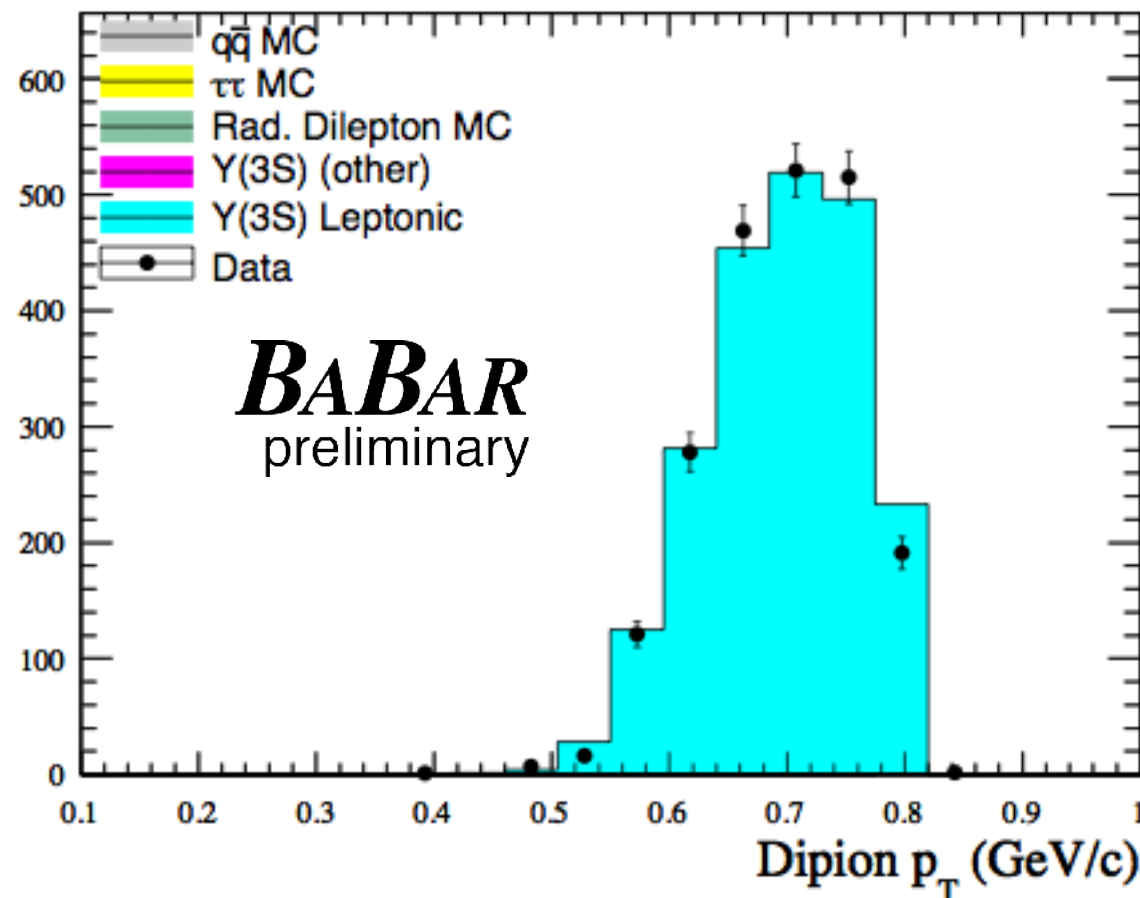
# Single Input Correlations with Recoil Mass





## 2 Lepton Data Set

- $p_T$  for 2 Lepton Data – Lower Statistics data set



# Loosening MVA Cut

- Changing the MVA cut to 0.1 gives a different distribution in these variables:

